160
39p.

(NASA SP-5006)
GPO: $0.30

N64-17838 *
CODE-1

TECHNOLOGY SURVEY

Technology Utilization Division

THE MEASUREMENT OF BLOOD PRESSURE IN THE HUMAN BODY

A state-of-the-art summary oriented toward nonmedical scientists and engineers

next p

NASA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

(NASA SP-5006) GPO: $ 0.30

TECHNOLOGY SURVEY

Technology Utilization Division

Title

THE MEASUREMENT OF BLOOD PRESSURE IN THE HUMAN BODY

By C. R. Smith and W. H. Bickley (Clyde Williams and Co.) 2470052

Apr. 1964 39 p refs

Prepared under contract for NASA
by Clyde Williams and Company,
Columbus, Ohio

Double code

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON, D.C. APRIL 1964

FOR SALE BY THE SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, D.C., 20402 PRICE 30C

FOREWORD

THE Administrator of the National Aeronautics and Space Administration has established a Technology Utilization Program for the rapid dissemination of information on technological developments which appear to be useful for industrial application. From a variety of sources, such as NASA research centers and NASA contractors, space-related technology is screened, and that which has potential industrial use is made generally available.

This publication, part of a series designed to provide such technological information, is a state-of-the-art summary prepared from the open literature. Developed to help Technology Utilization Officers in NASA field centers identify possible innovations that will contribute to the solution of the problems in the present methods of measuring blood pressure, it is oriented toward nonmedical scientists and engineers. It is being made generally available to provide perspective for other nonmedical technologists who may wish to apply their knowledge to life science problems.

DIRECTOR
Technology Utilization Division
Office of Technology Utilization and Policy Planning

CONTENTS

INTRODUCTION

THE MEASUREMENT OF BLOOD PRESSURE in the human body is probably the most widely used diagnostic tool in the practice of medicine today. Not only can malfunctions of the heart be detected through blood-pressure mensuration, but diseases of the blood-carrying ducts—arteriosclerosis (hardening of the arteries) and congenital cardiovascular anomalies, for example—must be substantiated by an accurately obtained blood-pressure record. Pulmonary and endocrine disorders, as well as those of the nervous system, can manifest themselves in blood-pressure variations, as can many other organic ailments.

Every physician, regardless of his specialty, uses blood-pressure interpretations to assist him in making accurate diagnoses. Doctors often remember the medical-school exhortation that "no patient is adequately examined unless his blood pressure is properly recorded." The fact that every astronaut is "plugged in" to a continuous blood-pressure monitoring system serves to emphasize the importance placed on this parameter of body performance.

That the heart was early understood to be the "pump of life," is indicated in ancient writings. The teachings of Socrates showed a surprising perception of the heart as a pump to circulate the blood to the organs and back to begin the trip again. Yet, despite the investigations over a span of some six hundred years and the recognized importance of the measurement of arterial blood pressure as a diagnostic tool for the past one hundred years, it has only been since the beginning of the twentieth century that physicians have been able to apply this knowledge effectively. In the previous century, physiologists were able to make fairly accurate measurements by inserting various devices into the arteries of their subjects which most often were dogs or horses. Through these primitive efforts have come many of the devices and techniques used thousands of times daily throughout the modern world.

The term "blood pressure" is generic and can be broadly interpreted to mean the outward force of flowing blood created by the pumping action of the heart. With the proper equipment, it can be measured in any part of the circulatory system: the aorta, large arteries, main arterial branches, terminal arteries (arterioles), and capillary beds as well as those channels which return the venous blood to the heart: the terminal veins, main venous branches, large veins, and finally, the *vena cavae*. The main difference between arterial and venous blood is that the venous blood is oxygen-poor. Thus, upon returning to the heart, it is pumped to the lungs for reoxygenation, then back to the heart, and finally out again as arterial or oxygen-rich blood.

Almost universally, the term "blood pressure" has come to mean the measurement of arterial pressure in the right arm; and there are sound medical reasons why this is so. A quantitative value can be obtained with a minimum of discomfort to the patient, and valuable physiological data concerning the functioning of the total cardiac system is provided.

Arterial blood pressure is determined by a number of factors. The most important of these include cardiac output, peripheral vascular resistance, the volume of contained blood, blood viscosity, and the elasticity of the arterial walls.

Clinically, it is common practice to gather data

throughout the cardiac system by both direct and indirect methods. In direct measuring techniques, the blood pressure inside the blood-carrying duct—actually in the blood stream—is measured. Indirect techniques measure some outward manifestation of the blood pressure and attempt to correlate it with what actually goes on inside the stream.

In the direct measurement of pressure, a catheter or specially designed tube is inserted into the blood stream or even into a heart cavity. The direct techniques, which have been applied to all components of the human circulatory system, are valuable primarily because of their accuracy. Widespread use has been limited, however, for the obvious reason of patient discomfort.

This report is exclusively limited to the measurement of arterial pressure. This is primarily due to the fact that the accuracy of the measurements made on arteries is greater because the signal is obtained closer to the point of generation—the heart. The signal becomes more diminished the further it gets from the pump; hence, there is little or no pulsation in venous blood flow.

In procedures where the measurement of arterial pressure is not made by standard direct or indirect techniques, a correlation between arterial-blood pressure and other circulation-related phenomena is sought.

A number of investigators have attempted, with little success, to delineate the blood-circulation system quantitatively in a mathematical equation. The French physicist, Fourier (ref. 190), contributed a mathematical technique to separate a complex wave form into simple sine wave components of various frequencies and amplitudes; analysis of heart sounds or pulse by Fourier's method would simply yield the family of sine waves and amplitudes required to produce the original signal. However, the body does not necessarily create the signals by combining the pure sine waves. A pressure function of time within any blood vessel fits into Fourier's fundamental expression, but an intricate biological system cannot be compressed within the limiting conditions for successful application of this mathematical principle. Despite the incomplete mathematical explanation of blood pressure, the contributions of mathematicians and physicists have been significant in the development of modern measuring devices.

The maximum or systolic blood pressure occurs during systole—the period of contraction of the heart during which blood is forced outward and circulation is maintained. The minimum value is the diastolic blood pressure, and it is reached during the period of diastole when the heart expands and fills with blood. The numerical difference between these values is the pulse pressure. A so-called pressure-pulse curve may be seen in figure 1. Here the systolic and diastolic pressures are seen as functions of pulse rate.

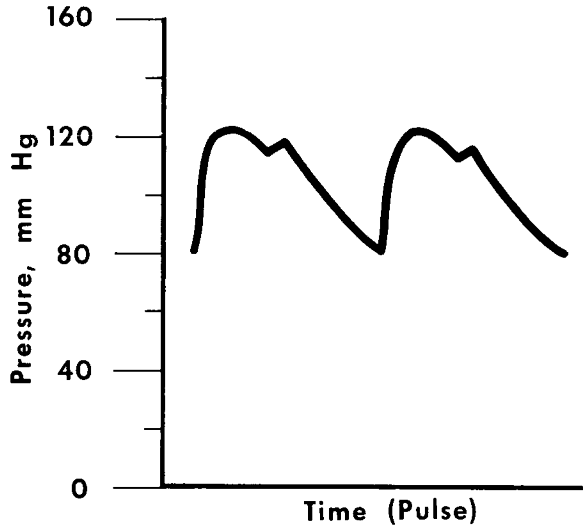


FIGURE 1.—Pressure-pulse curve for a normal heart.

The "mean" blood pressure is the average of all the successive pressures during each portion of the pressure-pulse curve. At first glance, the mean blood pressure would appear to be the average of the systolic and diastolic values, and in most cases it is nearly thus. Again, however, the complexities of the biological system prevent making such a bland statement without conditions. In a normal human, the mean blood pressure is not exactly equal to the average because the arterial pressure remains closer to the diastolic than systolic level during the greater portion of the cardiac cycle. The mean arterial pressure, then, is usually slightly less than the average of the systolic and diastolic pressures.

HISTORY OF BLOOD-PRESSURE MEASUREMENT

Devices for the accurate measurement of blood pressure and a qualitative understanding of the pressure phenomenon have existed only in recent years. The experiments of Stephen Hales, in 1732, are generally acknowledged to be the beginning of sound, scientific investigations (ref. 1). Hales, in his experiments with various animals, used a 9-foot length of glass tubing which was attached to a brass cannula by means of the trachea of a goose. The cannula portion of this unwieldy apparatus was then inserted into an artery. The animal's blood rose in the glass tube, oscillated, and fell, reflecting—even though crudely—the pulsating blood pressure within a close circulatory system. At best, the measurements of Hales were poor. Many problems arose from using the animal's own blood as the pressure-indicating medium—clotting of the blood and infection, primarily. Almost a hundred years later, Poiseuille (ref. 2) substituted a mercury-filled U-tube (fig. 2) for the long, glass tube and cannula. Bicarbonate of soda was used to overcome the problem of blood coagulation encountered by Hales. Poiseuille's device was called a hemodynameter, and, in this first practical instrument, blood pressure was expressed in millimeters of mercury.

Many specialists contributed refinements to early mercury instruments, but by 1875 considerable interest was expressed in metal manometers which could overcome the inertial problem of the mercury column. The Fick manometer, introduced in 1878, (fig.3) was called a federmanometer (from the German "feder," meaning pen). The blood pressure was transmitted through a tube to a metal diaphragm, which activated a

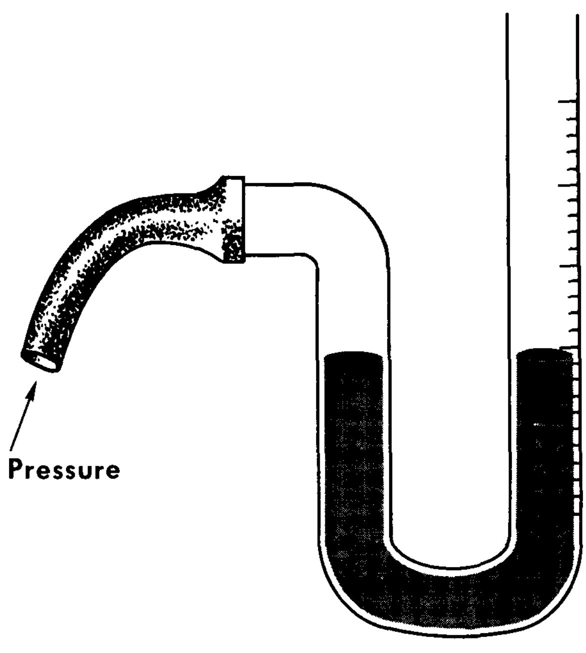


Figure 2.—The Poiseuille U-tube manometer. Arterial pressure, transmitted to the mercury-filled U-tube by rubber tubing, caused the right side to rise and the left to fall. The blood pressure is practically equal to twice the distance that the column on the right rose in millimeters of mercury. (The compression effect of the weight of blood on top of the left-hand column must be subtracted from the reading to realize the actual results.)

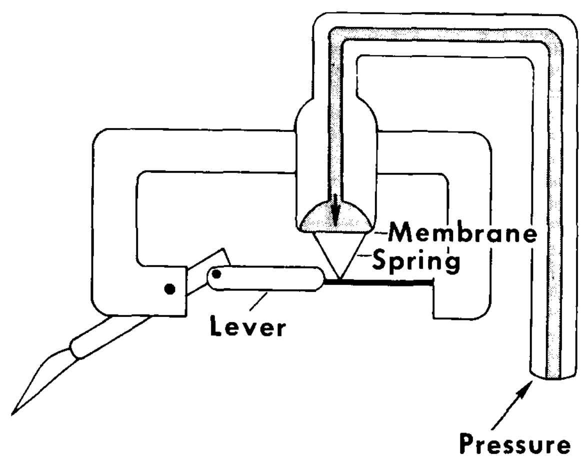


Figure 3.—The Fick manometer—one of the first mechanical pressure transducers. Blood pressure causes membrane to move, thereby activating spring and lever.

724-177 O-64-2

writing stylus. Hürthle, in 1888, introduced an important and extremely accurate spring recorder of essentially the same design as Fick's apparatus. The significance of these devices is that they were the first crude forerunners of today's pressure transducers.

All of these devices were designed for measuring blood pressure directly—actually within the arteries. Simultaneously, considerable interest in the development of indirect means of measuring blood pressure was developing.

In 1834, Hérrison perfected a device consisting of a membrane-covered bell and a capillary tube (fig. 4). The metal bell was filled with mercury, and, when the membrane was placed in contact with a radial artery, the cardiac fluctuations could be observed in the tube.

An important early series of experiments was conducted by Vierordt (ref. 4), whose technique was presented in 1855 and whose apparatus is illustrated in figure 5. Vierordt measured arterial pressure indirectly by measuring the counterpressure which would just obliterate the arterial pulse. This was one of the earliest practical sphygmograph instruments—designed to register the movements, form, and force of the arterial pulse.

Marey's work with the plethysmograph in the 1870's led to the principle and conditions of maximum pulsation of arterial walls. Marey's principle was a major contribution to the understanding of arterial pressure and modern devices for its measurement. It is stated thus:

> At the moment the pressure oscillations reach their maximal amplitude, the extravascular and intravascular pressures are equal and the walls of the arteries are relieved of intra-arterial and extra-arterial tension so that they pulsate maximally.

Concurrently with Marey's investigations, von Basch (ref. 6, 10) developed a primitive sphygmomanometer which established the basic principles for the modern instrument. (The term sphygmomanometer is derived from the Greek word "sphygmos," meaning pulse.) The accuracy of von Basch's instrument, however, was very poor. Its essential design is shown in figure 6. The pelote was filled with water, and, when pressed against an artery, transmitted the arterial oscillations to the mercury manometer. It was constructed of rubber with a membrane covering. In use, the pulsations of the artery—usually a radial artery—were obliterated by pressing the pelote against it. As the pressure was removed, the point at which the pulsations reappeared, as indicated on the manometer, was considered to be the systclic blood pressure. Von Basch later improved the design by incorporating an aneroid

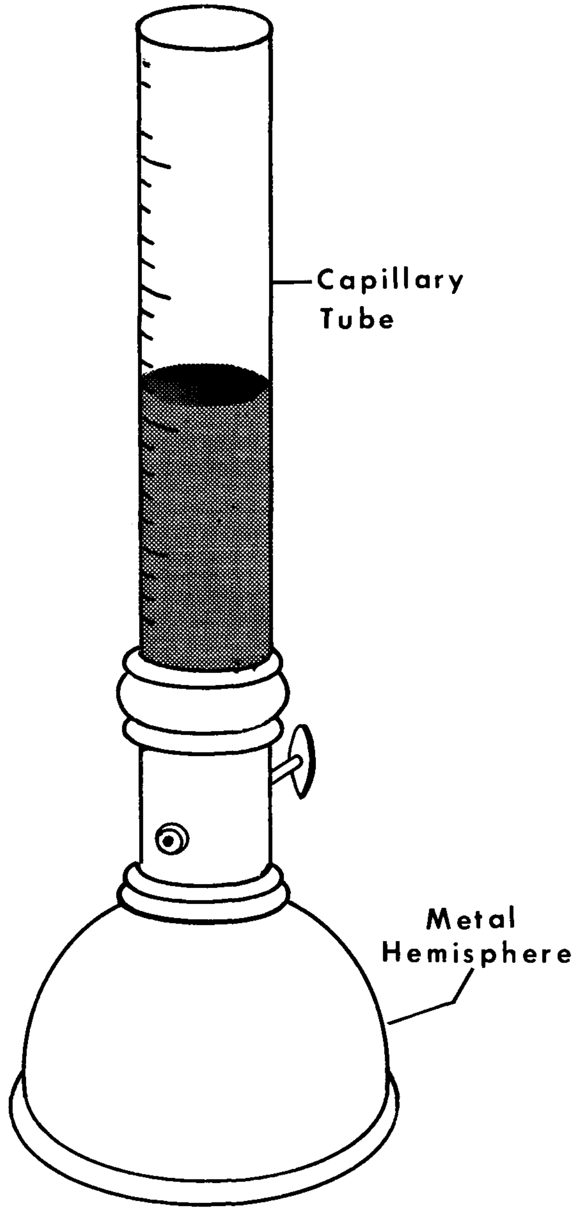


FIGURE 4.—The Herrison manometer. The capillary tube contained mercury. The metal hemisphere was covered with a membrane through which the arterial oscillations were transmitted.

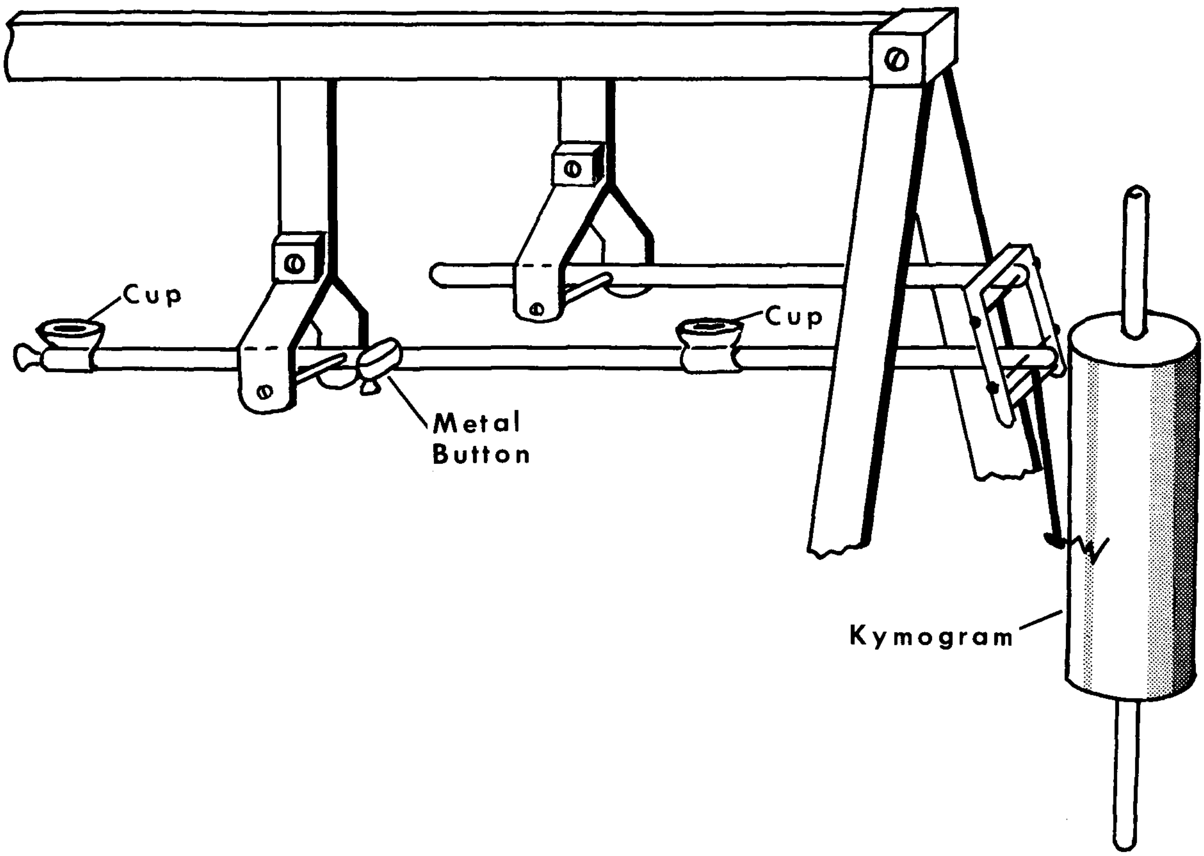


FIGURE 5.—The Vierordt sphygmograph. Metal button was placed over the radial artery. Weights were added to cups until the pulse was obliterated as indicated on kymogram.

manometer in place of the mercury-filled unit. Twelve years later, in 1889, Potain (ref. 11, 12, 22) improved the original design of the pelote and substituted low-pressure air for the water.

Toward the end of the nineteenth century, a number of experiments, based upon the counter-pressure necessary to obliterate the pulse, resulted in the development of several spring-gage devices. These offered considerable improvement over the lever-actuated system developed principally by Vierordt. But it was in 1896 that Riva-Rocci (ref. 18) introduced the blood-pressure cuff. A typical instrument using the cuff is shown in figure 7.

Undoubtedly, the most significant improvement in the design of portable, convenient blood-pressure measuring equipment, the pneumatic cuff has remained unchanged, in principle, to the present day. The cuff-sphygmomanometer was used to ascertain the pressure at which the pulse was obliterated—the systolic or maximum pressure. The minimum or diastolic pressure was determined by physical palpation of a radial artery and accepted as the point at which the pulse began to disappear.

Despite the existence of a relatively large number of experiments and devices, blood-pressure values were of little significance until the beginning of the twentieth century. The major problem was not so much with the equipment as with an understanding of the values obtained and their relationship to the actual or direct blood pressure. The maximum or systolic pressure was taken as that force required to compress the artery to a point where the pulse wave was just obliterated. In later experiments, however, it was concluded that the maximum pressure should be that value at which arterial pulsations just reappear when the pressure is gradually reduced

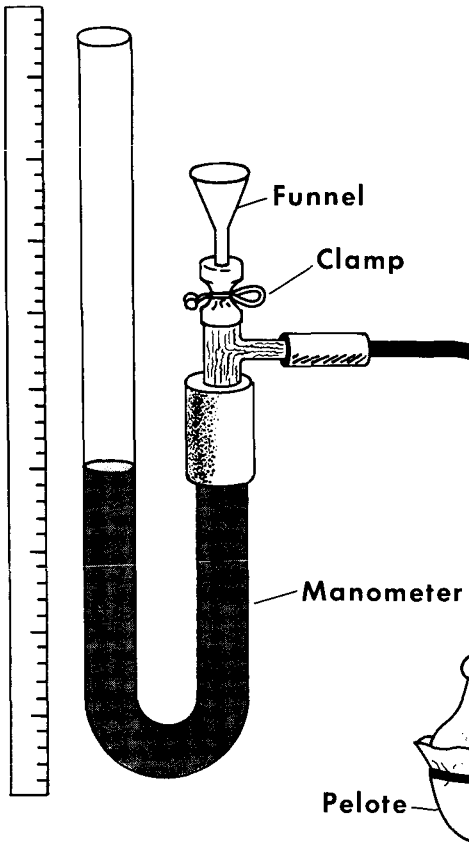


FIGURE 6.—The von Basch sphygmomanometer consisted of a manometer and a pelote which was filled with water through a funnel and then sealed with a clamp. The pelote transmitted arterial pulsations through the water to the mercury manometer.

after the pulse has first been obliterated by increasing the pressure.

An especially important contribution was made by the Russian scientist, Korotkoff, in 1905 (ref. 30). He classified the arterial sounds that he heard at a point directly below the cuff and over the artery. These sounds were originally separated into three phases, and later into five, based on interpreted aural phenomena. The importance of the Korotkoff sounds lies in the fact that they can accurately indicate the points at which the systolic and diastolic pressures had been reached. The systolic pressure is generally acknowledged to have been reached when the Korotkoff sounds first appear during pressure release—a sharp "thud" is heard. The diastolic pressure is somewhat more difficult to relate precisely, but the value is generally accepted to be between the fourth and fifth phases. The aural manifestation at this point is between a soft, blowing sound and total silence. Most experimenters believe that the sounds are caused by a sudden, vibrating rush of blood through the artery after collapse or pulse obliteration is over. Thus, the technique of using the Korotkoff sounds—the auscultatory method—is extremely important in modern blood pressure measurement.

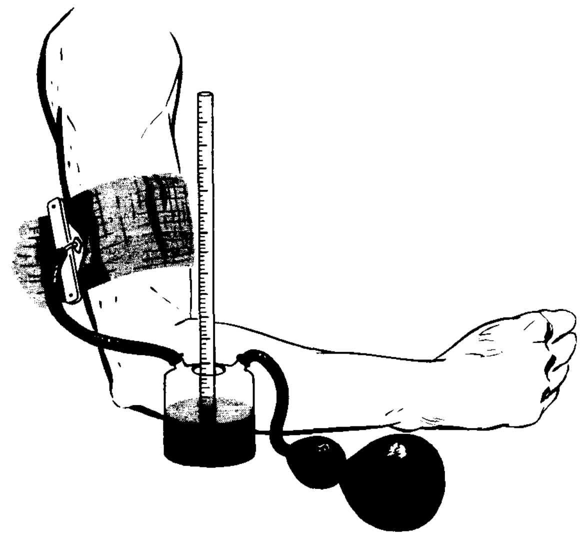


FIGURE 7.—The Riva-Rocci sphygmomanometer in which a pneumatic cuff was used to obliterate arterial pulse. A mercury manometer and reservoir were used to obtain the pressure reading.

TWENTIETH CENTURY METHODS

THE TWENTIETH CENTURY marked the beginning of the usage of sophisticated devices which have wide application in both clinical and research medicine. Refinement of components, rather than completely new measuring techniques, has been the principal research objective.

Direct Methods

Early in the twentieth century, the mercury manometers had begun to be completely replaced by low-inertia mechanical-lever systems utilizing direct read-out techniques. By 1925, Frank had begun experiments with a photographic-recording manometer employing a beam of light reflected from a mirror which was attached directly to the pressure membrane. Wiggers, Wolf, and von Bonsdorff also produced instruments based upon optical principles, and it was the work of the latter two (ref. 73), in 1931, that made possible the first accurate comparison of direct and indirect blood-pressure measurements. The indirect method used in their comparison test was the auscultation technique.

A metallic membrane was incorporated into an optical manometer by Hamilton in 1934 (ref. 82). Beyne and Gougerot further improved this device by making use of electronic amplifiers and a system of two membranes. A number of devices which operated by measuring resistance of capacitance change were introduced in succeeding years. Today, the most sensitive and accurate instruments incorporate strain-gage transducers.

Indirect Methods

During the fore part of the twentieth century, considerable refinement of indirect methods also took place. By the early 1900's, the technique of measuring the force of counterpressure required to just obliterate the pulse was generally accepted as the means of measuring systolic pressure. The most practical and accurate technique of doing so utilized the pneumatic cuff.

A modern sphygmomanometer is illustrated in figure 8. It consists of: a compression bag surrounded by a cuff for application of an extra-arterial pressure; a manometer by which the applied pressure can be read; an inflating bulb, pump, or other device by which pressure is created in the system; and a variable, controllable exhaust by which the system can be deflated.

Modern sphygmomanometers incorporate either the mercury manometer, such as that shown in figure 8, or an aneroid manometer, employing a metal bellows system. These devices, when properly maintained and carefully used, measure pressures accurately within 6 or 8 millimeters of mercury. The most distinct advantage of such an indirect system of mensuration is the elimination of the necessity for penetrating the blood stream with foreign objects, thus eliminating the risk of infection, as well as the accompanying patient discomfort.

There are a number of practical considerations when comparing the aneroid and mercury systems. The aneroid device is more portable but requires careful maintenance and adjustment by specialists. The mercury unit requires no recalibration, parts are easily replaced if broken, and the unit is extremely accurate. However, the components are bulky and prone to breakage.

Using the modern sphygmomanometers, it is possible to measure arterial blood pressure several different ways. The oscillometric method consists of occluding the artery and visually recognizing the return of the blood. The method is well known but seldom used in modern practice.

In the palpatory method, the radial or popliteal pulse is palpated and the rate and rhythm are noted. The pressure in the cuff is then raised about 30 millimeters of mercury above the point at which the pulse is obliterated. As the pressure

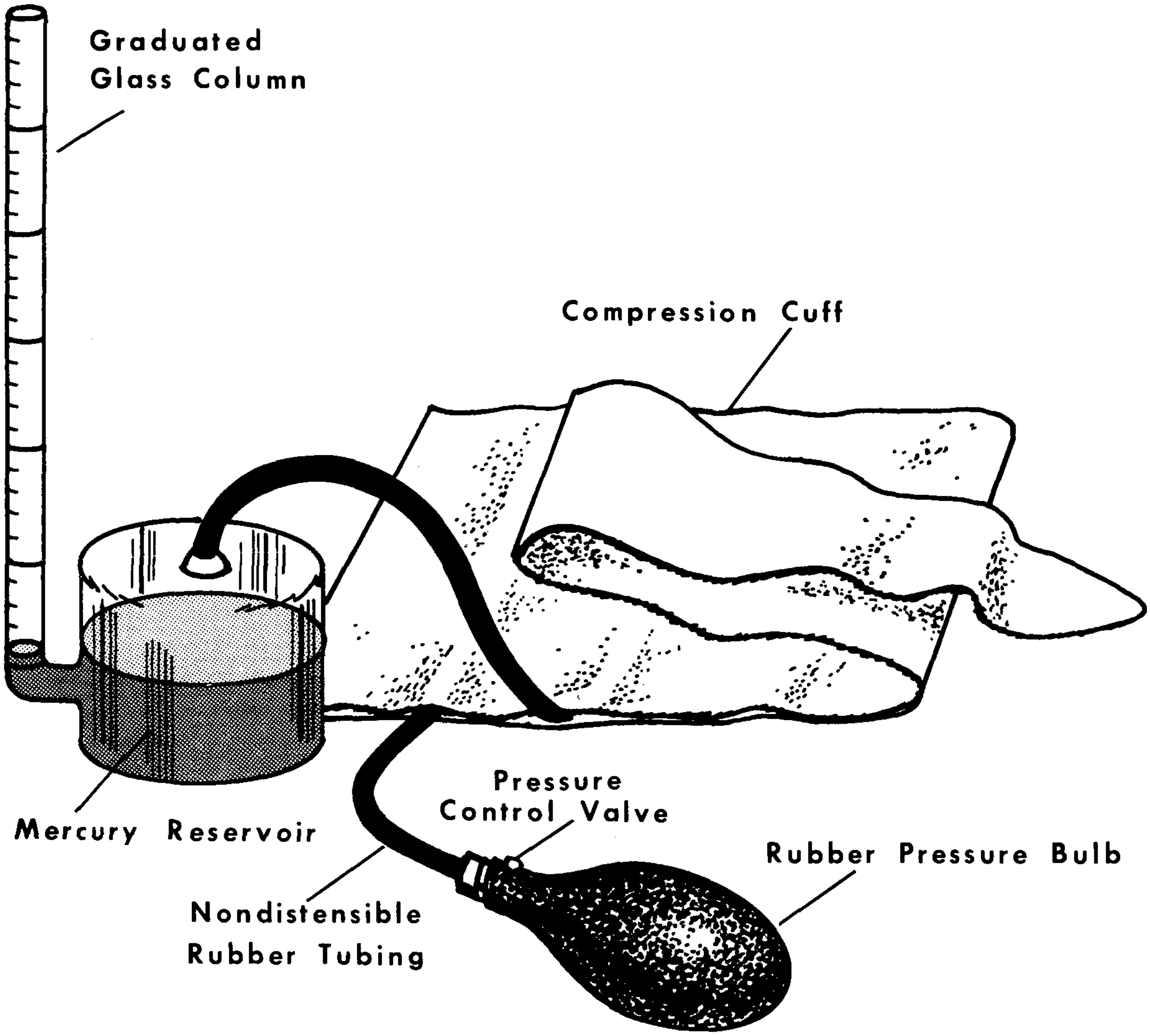


FIGURE 8.—A modern clinical sphygmomanometer.

is slowly decreased, the point at which the pulse just returns is considered to be the systolic pressure. The diastolic pressure is generally difficult to determine by this technique, although its successful measurement has been reported in isolated cases. A single snapping vibration superimposed upon the pulse, usually in the brachial artery, can be palpated as the cuff pressure is decreased. It occurs at a pressure which corresponds closely to the value of diastolic pressure obtained by direct measurement systems.

The auscultatory technique is dependent upon the Korotkoff sounds, which can usually be heard in the artery by means of a stethoscope placed immediately beyond the compression cuff—away from the heart. The pressure of the cuff is raised some 30 millimeters of mercury above the oscillation pressure and slowly reduced. An experienced "ear" can determine the systolic and diastolic values accurately, based on the quality and change of sound.

Determining arterial blood pressure by the flush method is especially useful for infants. Only the systolic pressure can be determined. In fact, some controversy exists as to whether the value obtained is actually closer to the mean-arterial

pressure than to the maximum pressure. An appropriate size cuff is placed around the ankle or wrist, and the limb is elevated and massaged to "milk out" the blood. When the limb has blanched, the cuff is inflated above the expected systolic pressure, and the limb is physically returned to heart level. As the cuff is deflated, the pressure at which the color begins to return is accepted as the systolic pressure.

Arterial Occlusion and the Korotkoff Sounds

The most widely accepted modern measuring techniques rely upon the ability of an externally applied pressure to collapse an artery (that is, to exceed the intraluminal systolic arterial pressure). Then, when the external pressure is slowly removed, a point is reached at which the blood pressure is just able to counteract the external force and open the artery, thereby permitting the flow of blood and the observance of the pulse below the point of occlusion (that is, on the side of the cuff that is away from the heart).

The arterial wall itself offers little resistance to compression, and, consequently, the blood pressure can be determined with relatively high-accuracy by measuring the pressure required to collapse the artery. When the systolic pressure slightly exceeds the occluding force (occluding force and arterial pressure nearly equal), a quantity of blood is ejected through the occlusion and produces the first phase of the Korotkoff sounds. As the pressure is further reduced, more blood flows, and the pulse becomes more apparent. With a further decrease in pressure, turbulence is reduced, and a definite interruption between the systole and diastole is observed; characteristic sounds diminish and finally disappear. Thus, the classification of Korotkoff sounds can be used to indicate the various stages of the pulse pressure and the resulting pressure waves. It should be recognized that not all the phenomena associated with the Korotkoff sounds are fully understood. However, the lack of a complete understanding of the turbulence effect and of the pressure waves has not hampered researchers in their ability to make them useful in measuring blood pressure.

During the past two decades considerable research has been performed in order to explain more fully blood pressure and the ways in which it can be more precisely measured and recorded. Particularly important has been the need to devise a system for automatic indirect measurement. The research scientist has generally followed two lines of exploration in this quest. First, there have been attempts to devise mechanical systems which can be connected to a modern cuff sphygmomanometer. The manipulation of cuff pressure and its graphic presentation, upon which is superimposed a visual presentation of Korotkoff sounds, have been reasonably successful and probably represent the most popular approach to devising an automatic system.

A second approach, and one which is advocated by an increasing number of researchers, is a system which will present systolic and diastolic pressures as a function of some other more easily obtainable physiological value. Research in this direction has delved into the relationship of pressure to stroke volume, oxygen content, pulse variations, and a host of other values which can be measured without hindering the physical activity of the individual. The optimum system must not only be automatic, but must provide a continuous record as well.

These—the development of a completely automatic measuring system and the relating of blood pressure to a more easily and accurately measured physiological parameter—are essentially the two broad goals of modern research in blood-pressure monitoring and measuring systems. At this time, however, systems and instrumentation do not exist which satisfy all requirements of chemical, electronic, and medical research efforts.

Since the 1940's substantial investigative efforts have been expended on the physiological factors of blood-pressure measurement. Of principal concern are those efforts associated with the indirect measurement of blood pressure in the human circulatory system.

In this application study, however, emphasis will hereinafter be placed upon recent advances in mensuration through improvements in arterial occulsion—that is, external compression and the accompanying auscultation of sounds. Techniques which seek to approach and solve the problem

of blood pressure measurement from an entirely different direction will, of course, be discussed in their proper perspective.

Automatic Monitoring Systems

The principal interest in blood pressure measuring devices today is twofold. First, there is a need for an improved clinical technique which can provide continuous monitoring over extended periods of time with little discomfort to the patient. And, second, it is extremely important that optimum systems be available for the physiological monitoring of astronauts, pilots, and individuals with similar responsibilities who must function under high-stress situations.

Various efforts at developing automatic devices can be traced to the early 1900's. Von Divingshofen is generally credited with the first in-flight attempt at recording arterial pressure. Others, such as Gibson, 1941, actually devised units which, though crude, did record meaningful pressure values. For the most part, however, it has been only in the last decade that devices with any degree of sophistication have been developed for either clinical or in-flight monitoring of arterial pressure.

Currently, there is considerable interest in the development of optimum systems, based upon either arterial occlusion or other correlated physiological information, to give meaningful blood pressure values. For example, instrumentation which would provide in-flight physiological data had been a primary concern of the Department of Physiology-Biophysics of the School of Aviation Medicine, Randolph Air Force Base, Texas—one of the nation's foremost bioastrionic research laboratories (ref. 277).

The earliest devices reported by this laboratory depended essentially upon the inflation of a conventional cuff. A microphone and transistorized amplifier recorded the Korotkoff sounds and a graphic comparison of the pressures so obtained could be made by superimposing the sound-wave tracing on the original pressure plot. The Korotkoff sounds were filtered to exclude as much outside interference as possible.

A description of the system, released in 1959, states that the blood pressures obtained in this fashion compare closely with those obtained by usual clinical methods. Actual tests made use of either a conventional or special thin cuff, designed for use with a pressure suit. A miniature, cam-actuated valve system inflated the cuff and then allowed it to bleed down lineally to room pressure.

The ear oximeter is a device which has shown the ability to provide a correlative value of arterial blood pressure. This instrument is essentially a photoelectric calorimeter for the determination of the percentage oxygen saturation of the blood contained in the intact ear (ref. 278, 279, 280).

The specific use of an ear oximeter in the measurement of arterial blood pressure was suggested by E. H. Wood in 1950. In discussing this device, Dr. Wood referred to a simple diagram of the earpiece and recording circuit similar to figure 9. In Dr. Wood's words:

> The pressure capsule, which is analogous to the pressure cuff of the usual sphygmomanometer, has two inlets, one for regulation and the other for recording of intracapsular pressure. The ear unit contains only one photoelectric cell rather than two; otherwise it is similar to the oximeter earpieces used for measurement of arterial oxygen saturation.
>
> Interposed between the source of light and photoelectric cell is the translucent pressure capsule with its two air inlets. Relatively small irises are placed at the ear end of the pressure capsule and over the photoelectric cell so that all the light reaching the photoelectric cell passes through the portion of the ear that can be efficiently pressurized by the pressure capsule. The single photoelectric cell can be connected either directly or through a condenser to a variable resistor and a sensitive galvanometer.
>
> When the instrument is used to record over-all variations in the blood content of the ear, that is, ear opacity, the condenser is removed from the circuit by using switch position 2 [in fig. 9] so that all the variations in the current of the photoelectric cell are recorded directly by the galvanometer. When the instrument is used to record the ear opacity pulse only, as is the case in the measurement of arterial pressure, the switch is opened (position 1). The currents of the photoelectric cell then must flow through the condenser which filters out the relatively low-frequency-current variations, due to over-all changes in blood content of the ear, and passes only the higher-frequency variations produced by the arterial pulse wave. The attenuation of low frequencies caused by insertion of the 12-microfarad condenser was approximately 50 per cent at one cycle per second (time constant 0.09 second).

With respect to the operation of the ear oximeter, Dr. Wood described its actual use and the results as follows (ref. 279):

> The ear capsule was inflated to a pressure of about 200 mm Hg, which completely obliterated the ear pulse, and then deflated slowly. The capsule pressure at the appearance of the first pulse was taken as the systolic pressure, and the

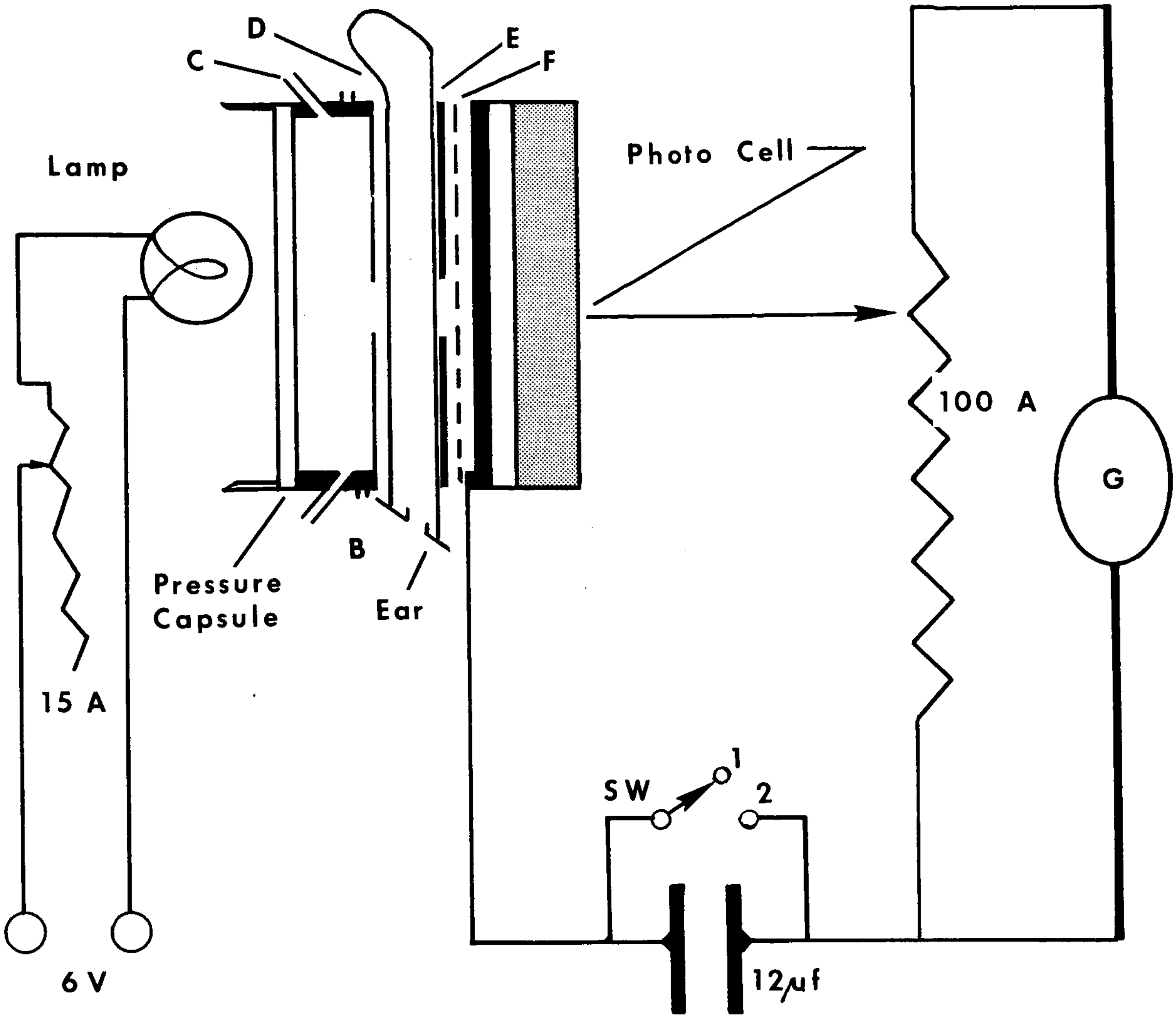


FIGURE 9.—Ear oximeter circuit. B, pressure inlet to the capsule for regulation of intracapsular pressure; C, pressure inlet for recording the intracapsular pressure; D, translucent rubber diaphragm covering the ear end of the pressure capsule; E, masking irises covering the ear end of the pressure capsule and the photo-electric cell; the diameter of the pressure capsule is 20.5 millimeters and of the irises 8 millimeters; F, double thickness Wratten 88A filter utilized for ear plethysmography; photo-electric cell, iron-selenium barrier layer, peak response at 800 millimicrons when used with double 88A filter; capacity of condenser, 12 microfarads; lamp, 6 volts, 0.2 ampere; G, galvanometer with sensitivity of 0.006 micro-ampere per millimeter and frequency of 5 to 10 cycles per second; switch position 1, ear pulse circuit; switch position 2, ear opacity circuit.

pressure at which the ear pulse attains its maximal amplitude was taken as the diastolic pressure. In the normal subject the direct pressure in the radial artery was 142 systolic and 73 diastolic, the simultaneous ear pressure was 145 and 64, and the indirect pressure determined by the usual auscultatory method was 105 and 66, all expressed in mm Hg.

Rapid repetitive determinations of systolic and diastolic pressure at the ear can be made by rapid reinflation of the pressure capsule each time the pressure decreases to the diastolic level. Thus a systolic and diastolic pressure reading was obtained approximately every ten seconds. The average direct pressure in the left radial artery in this subject was 130 systolic and 68 diastolic as compared to 130 and 70 at the left ear, and 108 and 60 by auscultation in the right brachial artery.

Recordings at faster camera speeds show the simultaneous pulse contours in the brachial artery, radial artery and at the ear during determination of the pressure at the ear. The correspondence of the contours of the pressure and opacity pulses was, in this instance, excellent.

The comparative blood pressure values obtained by simultaneous auscultation measurements made at the ear, and by direct puncture of the radial artery, all in the same seventeen subjects, are shown in Dr. Wood's work. The slope of the linear-regression line, relating auscultatory pressure to direct pressure, was significantly less than unity, which indicated that there was a systematic error in the systolic pressures determined by auscultation and that this error increased with the level of the pressure. The calculated correlation coefficients between direct, auscultatory, and ear pressures were not significantly different, however, being 0.98 for each of the sets of data. Apparently, therefore, by carefully controlling frequency, the pressure values obtained for blood flow in the ear are closely related to the intra-arterial blood pressure as determined by direct techniques. The physical configuration of the earpiece is also a variable and must be carefully designed.

Photoelectric techniques for the measurement of blood content and systemic arterial pressure may prove to be of value in certain types of clinical physiological studies. Further work with the oximeter, for example, will enhance the possibility that this device will offer an alternative method of monitoring blood pressure in a human being.

Schotz and his colleagues (ref. 280) verified Wood's work with the ear oximeter. They used a single-scale oximeter with a strain gauge connected to the pressure capsule. Sensitivity was set so that the full 50-millimeter scale represented oxygen saturation from 100 to 84 per cent. The authors are convinced that the oximeter, as a device to indicate changes in blood pressure, is a tool of great diagnostic potential and that refinement and further study will doubtless bring it to maturity.

Measurement of arterial pressure through correlation or comparison with other more easily obtained values has been the subject of concentrated investigation for many years. Specialists such as Erlanger, Hooker, Wiggers, Hamilton, and Starr have been extremely interested in deriving other factors of cardiac output from pressure values. In the past few years (ref. 283), investigators have re-examined the earlier work in search of new measurement techniques by working the original attempts in reverse. Starr and his associates (ref. 281), in 1954, developed empirical formulae by which the stroke volume could be derived from the age and blood pressure of the subject. By applying Starr's formula in reverse, a fairly accurate correlation can be determined if two limitations are considered. First, the correlation is likely to break down with high cardiac output. Second, the Starr formula shows many discrepancies when compared to auscultatory measurements, and, therefore, a reverse correlation is not well founded.

A detailed comparison, using the Fick method of cardiac catheterization on some 100 subjects, failed to show any comparable values. Quite to the contrary, the results strongly suggested that the discrepancies were completely random in nature and that the results, therefore, could not be improved by modification of the existing formulae.

Zuidema, Edelberg, and Salzman (ref. 284), reporting on their work in the Aero Medical Laboratory at Wright-Patterson Air Force Base, described a device using a conventional cuff inflated by an electric pump. A fluid-filled plastic balloon was placed beneath the cuff and directly over the brachial artery. The pulse waves were picked up by the balloon and transmitted through a fluid-filled polyethylene catheter into a Statham transducer. A great advantage of this type of system is the feasibility of making a single, relatively compact unit. Equally important, however, is that the pulse measurement and recording are almost simultaneous.

In ninety actual experiments involving ten men, the results from the automatic system showed a good comparison with those obtained using the auscultatory method. A correlation coefficient of 0.97 was determined. Futhermore, the authors reported a greater degree of constancy in the automatic measurements. The mean difference in systolic pressure was 1.1 millimeters of mercury while the standard deviation was 5.05 millimeters of mercury. In the diastolic pressure comparisons, however, a mean difference of 2.38 millimeters of mercury was obtained along with a standard deviation of 5.48 millimeters of mercury.

A typical oscillograph record of the Statham transducer readings is shown in figure 10. The systolic and diastolic pressures are indicated, and

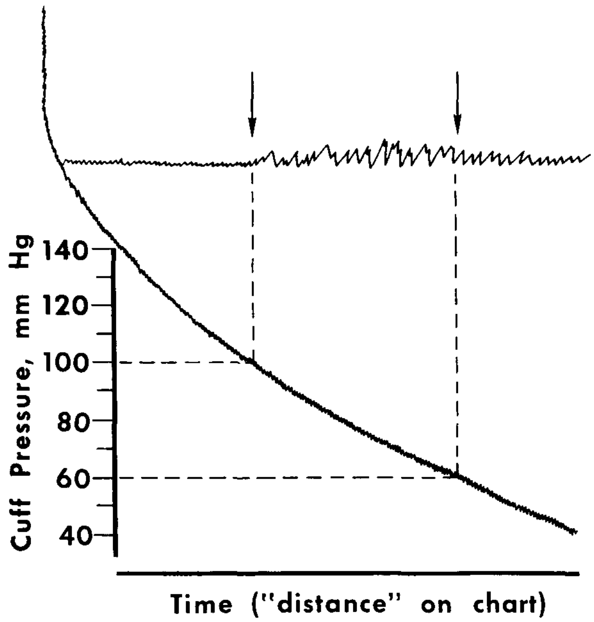


FIGURE 10.—Oscillograph record with systolic and diastolic pressures indicated (arrows). Dashed lines show how systolic and diastolic pressures are determined by referencing the cuff pressure.

the cuff pressure is calibrated as the ordinate of the plot. Dashed lines show how the systolic and diastolic pressures are determined by reference to the cuff pressure.

The same limitation which applies to the auscultatory method, however, applies to this automatic system, namely, the requirement of some 20 seconds to accurately determine systolic and diastolic values. While an entire operational cycle is approximately 25 seconds long, inflation of the cuff to 240 millimeters of mercury requires only 1 to 2 seconds.

In 1956, Zuidema and Edelberg (ref. 285) elucidated on a number of refinements in their "fluid-bladder" pulse-sensing device. Alterations were, necessitated because a vibration problem, originating between the bladder and the transducer, was encountered in tests conducted on the human centrifuge. Consequently, noise was produced in the oscillograph record. The vibrations caused the development of a one-piece balloon-and-tubing unit, encased in a lead tube—an arrangement which yielded superior oscillograph records.

Other modifications were also incorporated into the device, including a strain gage mounted directly on a thin metal plate. This unit, placed over the brachial artery and connected to a dc amplifier, led to significant improvement in high-altitude test-chamber performance. Previously, using a water-filled plastic bladder, leaks and artifacts had occurred.

Workers at the University of Michigan Medical School (ref. 286) designed a blood-pressure measuring device which could be used by a relatively unskilled subject. The principal interest in the program was centered around the recognized need for daily blood-pressure readings in connection with outpatient ailments such as hypertension. The Propper Company of Long Island, New York, developed the device for economical layman use. It is, primarily, a cuff which, when the proper size has been determined, can be slid on and off like a bracelet. A gauge and long connecting manometer tube are attached, and a stethoscope end piece is incorporated in the cuff. A binaural stethoscope can be easily connected to obtain Korotkoff sounds. The device has been deemed satisfactory in practice and can be readily manipulated by a medically untrained person—a layman—despite the propensity of such a person to make "inexperience errors," such as improperly deflating the cuff between readings.

Because of the simplicity of operation, a number of novel uses are possible. These include operating-room use by busy anesthetists and nurses and recovery-room application—possibly even where blood pressures may be monitored remotely by telephone-type hook-ups.

The use of a sensitive microphone to establish the systolic and diastolic pressure points has been described by Currens and his associates in work which they conducted at the Massachusetts General Hospital (ref. 287). A rubber bag, similar to the standard cuff and with a pocket at the distal edge, was designed. A crystal microphone, 32 millimeters in diameter and 9 millimeters in depth, is placed in the pocket, directly behind a diaphragm, and, when the cuff is placed over the arm, the microphone overlies the brachial artery, close to the antecubital fossa.

The cuff is inflated automatically, and the pressure is recorded on a milliammeter. At the first Korotkoff sound the recording needle is

deflected, superimposing a discrete "pip" on the pressure curve. According to the authors:

> As the diastolic pressure is approached, the vibrations become swollen, and there is usually a distinct change in the amplitude of the deflections on the graph. The point of maximal change of this deflection is considered to be the diastolic blood pressure.

The cuff pressure transducer consists of four sensitive resistor elements mounted in a bridge circuit. The bridge is balanced at zero pressure and voltage is supplied by a 200-cycle-per-second audio-oscillator. The voltage changes are amplified, rectified, and transmitted to a mixing circuit. Examination of the voltage waves projected on an oscilloscope screen shows little or no output from the microphone until the Korotkoff sounds are heard. The output increases until the maximal change in sound and then decreases abruptly.

Owing to a low-frequency vibration from the normal blood flow in the artery, the microphone output does not drop to zero at diastole. The pressure wave below diastolic pressure level is eliminated so that a signal can be obtained which is related to the actual sound that is heard. This is accomplished by differentiating the electric signal before amplification and rectification.

In order to establish the accuracy of their device, the authors tested 52 patients, obtaining a total of 292 measurements. A physician and his students made auscultation measurements at the same time as the automatic equipment was monitoring the Korotkoff sounds. The results showed the systolic pressure obtained by auscultation techniques was 0.2 centimeter of mercury lower than that observed through the machine plots, and the diastolic pressure was 0.4 centimeter of mercury higher than that observed via the automatic equipment. Measurement of the pressures in centimeters of mercury was chosen, of course, for reasons of accuracy.

The authors state that their automatic unit has been used extensively with actual patients for continuous automatic nocturnal recording and in cases of hypertension. It has also been used where "pulseless disease" has made the usual clinical methods useless. Satisfactory service with newborn infants and with such clinical phenomena as pulsus paradoxus and pulsus alternans has been obtained.

In 1959 Systems Research Laboratories, under contract to the Aerospace Medical Laboratory, developed the relatively small, completely transistorized model 16 automatic blood pressure measuring instrument. R. A. Johnson (ref. 288) suggests that the 35-round unit could be battery-operated and miniaturized. Transistor logic for performing the program functions is considered a unique characteristic of the system. Johnson states ". . . the readouts are reliable and accurate." No comparative data have been reported, however.

The Model 16 has two sensing elements—one for pressure and the other for sound—mounted in a shoulder-supported cuff. Sequentially, the unit operates thus: first, the cuff is inflated rapidly to a preset value which is lower than the anticipated diastolic pressure. The cuff pressure continues to inflate at 2 millimeters of mercury per second and separately monitors or inspects for arterial sound variations. When a sound is properly identified (as that corresponding with the diastolic pressure), recording and telemetry equipment is activated. Immediately following this signal the cuff is further inflated to a preset level assumed to be above the systolic pressure. The pressure is then automatically decreased at the rate of 2 millimeters of mercury per second, and, again, the sound sensing unit is activated.

When the correct arterial sound is obtained, corresponding to the systolic or diastolic pressure, a 1.5-second timer is started, which coincides with an inspection for a second coincidence pulse. If the time interval is reached prior to the second coincidence pulse, the programmer reverts back and continues to search for the correct value. Tests can be automatically repeated at variable intervals from one to fifteen minutes.

The use of a photo-sphygmometer was reported in 1959 by Robinson and Eastwood (ref. 289). Their device, similar in many respects to other digital measuring units, utilized a pressure cuff in conjunction with an electronic detection and indication system. Using the principle that even the very slight fluctuations of blood within a vascular network may be detected through changes in the transmittance characteristics of a beam of light passing through the network, the unit employs a sensitive crystal photocell, a low-intensity light source, and an amplifier.

The tip of the finger, including the area of the nail, is ideally suited for measuring blood pressure by this technique; hence, a small finger cuff was readily adapted. The photocell-lamp assembly is slipped onto the finger and the light intensity adjusted to the point where the blood fluctuations are readily observed. The cuff-operation technique remains essentially the same—pressure is increased and then slowly released as the measurements are sought.

The authors point out the potential of the system for use where blood pressure cannot be readily determined by auscultatory methods. These include cases of hypotension, times when extracorporeal circulation is being used, and measurements on infants. Placement of the photocell-lamp is not critical, and there is no patient discomfort. Since vascular spasms may be expected to disrupt the measurement or make fluctuations hard to detect, a finger block is suggested.

Traite, in unpublished work in early 1961, theorized about a new device which could provide accurate and rapid pressure readings. The proposed device—one which would provide more than one reading per minute—would consist of a pressure cuff, inflated by a variable speed motor, and a piezoresistive displacement-plethysmogram pick-up on an appropriate finger. The slope of the plethysmogram envelope is used to detect the times at which the systolic and diastolic pressures occur.

Traite points out specifically the following features of the plethysmogram:

1. Its amplitude is constant below the diastolic level.
2. The plethysmogram amplitude decreases smoothly as pressure rises from the diastolic to the systolic and increases smoothly as pressure drops from the systolic to the diastolic.
3. The plethysmogram amplitude is constant (zero) above the systolic level.

As diagramed in figure 11, a narrow-band amplifier (1 to 2 cycles per second) is used for the plethysmogram. The signal passes through a peak detector to produce an envelope—a differentiator so that the slope may be determined—and to a Schmitt Trigger. An integrative inverting amplifier completes the processing of the signal.

The cuff is cycled between the systolic and diastolic pressures only. Each time that a "spike," or discontinuity is detected on the differentiator plot, the pressure system is revised. On the basis of normal blood pressure lying between 80 and 120 millimeters of mercury and a pressure rise-and-fall rate of 5 millimeters of mercury per second, a series of complete recordings could be obtained at approximately 8-second intervals. In practice, because of the time constants necessary for peak detection and differentiation, the wave forms would not be as clear and sharp as in the ideal case. These time constants would also introduce some delay between the ideal and practical wave forms.

The Schmitt trigger circuit would be valuable in "squaring up" the practical slope and should produce a clear, sharp signal for the pressure-reading mechanism. The integrating, inverting amplifier would control the speed of the motor and, consequently, the air compressor, thereby controlling the rate of rise and fall. A constant rate of pressure rise and fall is not a critical factor in the system as long as it is within reasonable values.

It was also determined experimentally that a sharp restriction in the allowable band width of the plethysmogram pulse overcomes the motion artifacts normally encountered in using this device. The fidelity of the pulse is lost by this restriction, but the relative amplitude is retained and the susceptibility to motion is almost completely eliminated.

Late in 1962 a pressure-measuring device, which utilized a piezoresistive sensor and an amplifier in conjunction with a finger cuff to provide a plethysmogram, was described by Traite and his associates at the 15th Annual Conference on Engineering in Medicine and Biology (ref. 290). The pressure cuff is inflated at 5 millimeters of mercury per second. With cuff pressure below diastolic level, a repetitive plethysmogram is shown by successive beats; the main pulse and dichrotic notch are exhibited. At pressures exceeding the diastolic, the notch pulse record flattens out and broadens. Sample-and-hold circuits are activated at this point and at the systolic pressure level, which is determined to coincide with the point at which the main

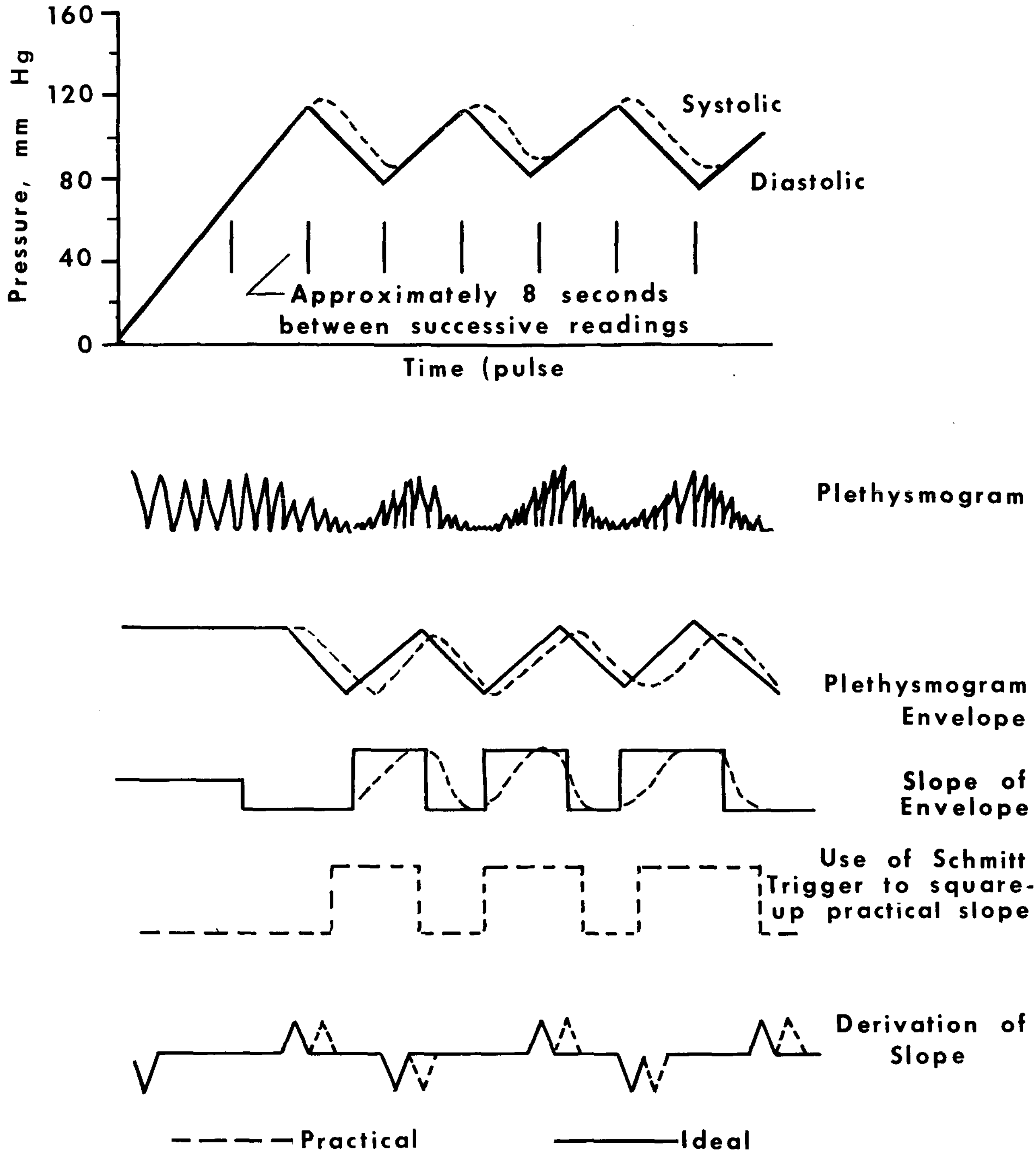


FIGURE 11.—Interpretation of a plethysmogram.

pulse disappears. At the proper moment, the cuff vent circuit is activated automatically and the cycle starts over. Test subjects reported that the repetitive cycle is largely ignored after 5–10 minutes. The authors state that correlation with standard brachial-artery pressure measurements is within 5 millimeters of mercury.

Concurrently with Traite's work, London University announced the development of a finger-cuff device for measuring blood pressure

over prolonged periods of time (ref. 291). The British device, designed at the Postgraduate Medical School, utilizes two thin rubber cuffs which fit tightly around one finger. One is inflated to occlude the main finger artery while the other cuff—the one closest to the end of the finger—senses the arterial pulsations. These pulsations are transmitted through a polyethylene tube to a photoelectric transducer, amplified, and recorded by a hot-wire pen on heat-sensitive paper. According to the developers, these finger cuffs have proven comfortable to sleeping patients for extended time periods.

During operation, the distal or sensing cuff is kept at a pressure of about 20 millimeters of mercury. As the pressure in the occluding cuff falls below the systolic pressure, the pulsations are picked up in the sensing cuff of the instrument.

A double Perspex chamber is used in the optical transducer system of the British device. A controlled leak allows the pressure in the two sides of the chamber to equalize over a period of time, but if the change is rapid, such as that caused by the pulse frequency, the diaphragm is moved and the cadmium sulphide photoconductive cell is illuminated via a mirror system.

Earlier work (ref. 292) indicated that a fairly elaborate console unit is needed for the circuity, pump, and recorder. The accuracy of the systolic values depends upon the sweep rate of the pen and the pulse rate of the subject. More accurate readings are obtained for the faster pulse rates. The English-developed device is not recommended for obtaining diastolic readings.

NASA'S ROLE IN BLOOD-PRESSURE MONITORING RESEARCH

A DECISION WAS REACHED by the National Aeronautics and Space Administration in April of 1961 to include a blood-pressure monitoring device in the space capsule to be used in the first United States orbital flight (ref. 293). After examining the state of the art, it was decided that a method under development, similar in principle to modern sphygmomanometry, would be used. The system employed an occluding cuff on the left arm. A sensitive microphone under the cuff, overlying the brachial artery, picked up the Korotkoff sounds.

NASA identified a number of problems to be considered in system design:

1. Pilot safety and comfort
2. Establishment of the accuracy of the measurement compared to clinical and direct methods
3. Operation in full-pressure suit
4. Operation on an active subject in a noisy environment
5. Compatibility with spacecraft systems
6. Compatibility with the receiving facilities at Mercury Control Center and the Mercury Network stations.

The original idea was built upon the concept of a fully automatic pressure-monitoring system which could be operated by the ground control station or by the pilot. Special safety circuits would release the cuff pressure if it remained above 60 millimeters of mercury for longer than 2 minutes. Cuff pressure could be reduced linearly, from 220 to 60 millimeters of mercury, by a special regulator in which a motor-driven cam varied the reference-spring tension. The pneumatic system is described as

> consisting of an oxygen storage flask, solenoid fill valve, motor-driven regulator, dump solenoid valve, cuff pressure transducer, and suit reference manifold. The regulator, dump solenoid valve, and pressure transducer were referenced to a manifold connected through a flow restrictor to the pressure-suit system to prevent differences between cabin pressure and suit pressure from causing large errors and to allow continuing measurements in the event of the loss of cabin pressure.

Of special importance is the cuff which is utilized in this system. NASA engineers concluded that the cuff would have to be worn inside the suit because of the large errors apparently caused by the suit-cooling ducts. The pneumatic line used to inflate the cuff required extensive development.

The line was constructed of neoprene with special fittings for spacecraft egress. An entirely new cuff was developed and tested because of the stiffness and bulk of the standard 5-inch cuff and because it restricted arm movement. The new cuff was constructed of nylon and Velcro, was almost unnoticeable when uninflated, and provided accurate data, which were comparable to those obtained by more conventional means. A potentiometer-type transducer (1.5-volt output) supplied the cuff-pressure information to the telemeter.

A specially damped piezoelectric microphone was developed with a signal filter for the 32- to 40-cycle-per-second operating range. The microphone was 3.5 centimeters in diameter and 0.5 centimeter thick. The unit is so constructed that the sensitivity to sound coming from any direction except from the skin is at a minimum.

The microphone signal is transmitted to an amplifier system consisting of a shielded preamplifer and two high-gain amplifiers. Filtering the signal to the 32- to 40-cycle-per-second range is accomplished by resistor-capacitor filtering circuits in the feedback loops. The amplifier output is minimum-gated for reduction of output-noise level and improvement of the signal readability. The microphone signal and the signal from the pressure transducer are mixed in a minature transformer. Clipping circuits are incorporated to eliminate excessive voltages and cross-channel interference.

A number of problems arose in adding the entire system to the spacecraft, since it was, in reality, an afterthought. Consequently, the automatic inflation components were discarded, and a simple hand pump and cuff valve were used. (The automatic inflator, gas source, and motor programmer were planned for use in subsequent flights, however.)

A series of extensive tests were conducted on the complete system to determine reliability and accuracy. A special unit was added to the human centrifuge at the University of Southern California. Individuals with the cuff apparatus on the right arm and arterial catheters inserted into the left arm were tested at various acceleration speeds. It was determined that the indirect pressure readings were approximately 5 millimeters lower at systole and 5 millimeters higher at diastole as compared to the direct readings.

The conclusions reached were that the newly developed system closely reflected the direct arterial reading and that the 5-millimeter differences were probably due to the increased sensitivity of microphone over stethoscope.

An unpublished report prepared for NASA's Project Mercury by Webb Associates in 1961 summarized the primary research efforts on arterial occlusion measurement methods which were underway at that time. For the most part, the information obtained by Webb Associates was unpublished at the time their report was being prepared, and the information, therefore, represents progress in various stages of research. It should be recognized that the majority of research efforts are privately funded and are not now—and probably will not be—generally available. Furthermore, because of the state of the research progress, detailed research reports were unavailable to Webb researchers.

Webb Associates reported that at least seven companies were producing automated blood-pressure devices suitable for clinical use. For the most part these automated units monitor the systolic pressure only and are probably unsuited for in-flight use.

Several devices which could be used in flight, however, had been developed at the time of the 1961 Webb survey and were physically located at:

School of Aerospace Medicine, Aerospace Medical Center, Brooks Air Force Base, Texas

Ames Research Center, NASA, Moffett Field, California

Edwards Air Force Base, California

Wright Air Development Division, Bioelectronics Section, Wright-Patterson Air Force Base, Ohio

AiResearch Manufacturing Division, The Garrett Corporation, Los Angeles, California

Systems Research Laboratories, Dayton, Ohio

All of these units employed a microphone pickup conjunction with an occluding cuff.

The School of Aerospace Medicine (SAM) at Brooks Air Force Base, Texas, has pioneered a number of physiological studies and is reported to be well advanced in medical flight instrumentation. In 1961, two F-100 and one TF-102 jet

aircraft were equipped for in-flight blood pressure measurements with units which were small enough to be included in the seat kit. However, still further miniaturization was thought to be possible. In addition, the SAM was reported to be doing work with the detection of the arterial pulse by photoelectric devices.

A device which is fundamentally an improved version of the SAM unit was reported undergoing tests at Ames Research Center during preparation of the Webb survey. Consolidated Electrodynamics' Datalab Division reportedly had made recommendations on size, reliability, and circuity. Additional improvements in the microphone pickup system were also reported to be necessary.

A unit developed by AiResearch was said to be particularly unaffected by environmental sound. A direction-sensitive contact microphone and narrow filter appeared quite desirable, and adaptation of the device to the Mercury Space Capsule was said to be under way at the time.

A theoretical technique proposed by the Carleton Aviation Company of East Aurora, New York, was being considered by NASA during preparation of the Webb report. The unit was to be a completely pneumatic system for control of cuff pressure, and compressed gas would be used to operate the programmer.

In late 1961, the Bioastrionautics Section of the Boeing Airplane Company indicated that it had a prototype device under development for the measurement of blood pressure. A mechanical tensor, which would replace the pneumatic cuff, was one of the primary goals of the program. Webb Associates also learned that Ames Research Laboratory and Stanford Research Institute were also expending efforts to eliminate the occlusion cuff by using a sensitive capacitance pickup.

DEVELOPMENT OF UNCONVENTIONAL TECHNIQUES

In a review of both direct and indirect blood pressure measuring techniques, presented before the Fourth International Conference on Medical Electronics, H. W. Shirer (ref. 294) discussed an "Indirect Unloading" technique. While the method has not been fully developed, the author indicates that considerable promise is held for obtaining much of the information of the vessel-puncture method without the accompanying serious problems.

The technique is based on the assumption that all tension can be removed from the blood-vessel wall and that, by enclosing this vessel within a chamber, the vessel wall can remain unstretched over the range of endovascular pressure.

As liquid is added to the chamber, the chamber pressure increases and, consequently, reduces the volume within the vessel and the vessel diameter. A point will be reached, according to this theory, at which all tension is removed from the vessel wall—that is, the chamber pressure equals the endovascular pressure. Thus, the pulsating pressure in the chamber will be maximum and equal to the true pulse pressure. A slight further addition of liquid will have a negligible effect on chamber pressure, but it will reduce the volume occupied by the vessel.

The chamber pressure will rise in proportion to the amount of liquid added when sufficient liquid has been added to just collapse the vessel during diastole. The pulse pressure decreases and falls to zero when sufficient liquid is added to occlude the vessel over the entire cardiac cycle.

A number of limiting factors are pointed out by Shirer, including the problems posed by other tissue within the chamber and consequent chamber compliance. Viscous resistance of this tissue and of the chamber liquid, coupled with congestion of the collapsed veins during extended periods of recording, offer variables which must be overcome. Most of the more limiting problems of vessel puncture techniques have been overcome,

however, even though considerable research must still prove the practicality of the technique.

The concensus of a great many medical research specialists may be summarized by the statements of Adams and Corell (ref. 295) at the Thirteenth Annual Meeting of the Society for Vascular Surgery, June 7, 1959:

> First, all of the presently available indirect methods of recording blood pressure are based on arterial constriction, and at end-point are identical to the clinically applied method of sphygmomanometry. Second, most cannulation methods are capable of yielding accurate clinical and research data, but are cumbersome and slightly hazardous. Third, these two techniques have been studied until it would appear that little is to be gained in further attempts to improve them. Fourth, and finally, if there are advancements to be made in ease or accuracy of blood pressure recording, it seems as though some new approach to the problem must be found.

As the authors pointed out in their presentation, the identification of a measurable parameter of the cardiovascular system, which varies as a function of arterial pressure, could facilitate measurement techniques which have an accuracy equal to intra-arterial values but which are not so undesirably secured.

Adams and Corell suggest that such a parameter does exist and that if one measures arterial volume, for example, and correlates the volume measurements with pressure, the resulting relationship is one of close correlation, even under dynamic conditions. The functional relationships vary from one patient to another but this can be resolved.

For an individual monitoring system it would appear quite likely that, by accurately establishing arterial pressure by clinical methods, a correlation with another value—say, arterial volume—could be established. The indirect pressure could then be determined by simple instrumentation based upon the relationship.

The authors state that the relationship between volume and pressure is quasilinear and the slope of the curve—and one point on the curve—establishes the correlation:

> Mathematically, the functional relationship between pressure and volume can be given by the formula pressure (P) equals slope (M) times volume (V) plus a constant (b). The constant is defined by the point on the curve, and herein must be zero.
>
> A calibration procedure was developed which determines these two mathematical characteristics for each case: Pressure Change (ΔP) = Density (p) x Level Change (h)
>
> (Based on blood specific weight of 1.057)
>
> $\Delta P = 0.74$ mm Hg per centimeter of Level Change
>
> Thus 33.8 centimeters of level change induces a mean blood pressure variation of 25 mm Hg.
>
> A priori, a pressure change is induced within an artery by elevation of the arterial section with respect to the heart; that is, by displacing the arm vertically by 33.8 centimeters, a pressure change of 25 mm Hg will be induced. Experimentally, this has been verified to within 2 to 5 per cent. Furthermore, the pressure in a downstream section of an occluded artery will be atmospheric pressure. Therefore, a method exists for establishing the slope of the curve and of one point on the curve, which is the zero point.

In the course of the authors' work, a capacitance transducer was designed to measure an output signal when placed over the brachial artery. One plate of the transducer device was constructed of a thin plastic material, vacuum-coated with aluminum. This membrane has a low modulus of elasticity and pulsates with the pulsatile variations of the surface tissue. The second plate is fixed, and the pair then forms a variable air gap capacitor whose capacitive variance is related to the surface distentions of the underlying tissue. In experimentation with variations of this device, it was found that the transducer position greatly affects accuracy, but when properly placed, the trace from the capacitance system is in close agreement with values obtained from intra-arterial techniques.

The possibility of measuring blood pressure by a correlation with pulse-wave velocity measurements was proposed by Salisbury and Wichmann (ref. 296) to a conference of the Instrument Society of America in September of 1961. Previous investigations have established certain relationships about the rigidity of artery walls when the pressure within the artery increases. Other investigations have established that the velocities of the blood-volume pulse and the blood-pressure pulse (the two are not identical) are in direct relation to the stiffness of the artery wall (ref. 297–300).

Salisbury and Wichmann suggested that a definite relationship exists between blood pressure and pulse-wave velocity which may facilitate measuring techniques without the inherent disadvantages of the cuff and sphygmomanometer procedure.

The two techniques proposed by the authors are based on the fact that any segment of a pressure-pulse wave contour can be labeled by brief,

superimposed square waves which modify the outline of the pressure pulse. The modified pulse wave propagates centrifugally, and its outline can be recorded distally.

The first method would impose a brief monitoring square wave upon the systolic peak of diastolic plateau. The time interval between the imposing of the monitoring wave and its arrival at a distal sensing device is measured, and the arterial blood pressure can be mathematically derived from it.

Salisbury and Wichmann also proposed a second method for measuring blood pressure. It is used to measure the amplitude of the applied pulse which is required to produce a noticeable effect on the pulse-wave contour recorded at a fixed distance, distally.

Short pulses, in the 20- to 50-millisecond range are applied to the systolic or diastolic phase. As the amplitude is increased, a point is reached at which the most distant strain gage is activated. The observed pulse is amplified and used to stop the amplitude increase of the applied pulse at a value just sufficient to "notch" the pressure-pulse wave. However, the flow of blood is not impeded.

In an illustration of a possible device, air pressure is used to generate the applied pulse. A strain gage detects the appropriate phase of the blood-pressure wave and triggers the pulse generator. The pulse is applied by momentarily opening a valve with a solenoid. The pulse amplitude, however, is controlled separately by an electromagnet connected to an air control valve which ultimately controls the amplitude of the applied pulse.

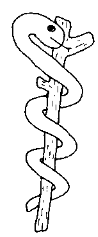
The strain gage in the second transducer detects the applied pulse, amplifies it, and feeds it inversely to the amplitude control, thereby reducing the current in the electromagnet. This current is proportional to the arterial pressure and can, therefore, be applied to a recorder in some fashion.

The two methods can be theoretically used to make blood-pressure measurements at the systolic, diastolic, or any other phase of the pulse wave. When both systolic and diastolic values are measured, separate channels are needed for each phase.

The authors summarize the advantages of the first method over the second thus:

> . . . it makes use of the strong dependency of applied pulse speed on pressure. The applied pulse must be very short since the accuracy of the pressure measurement is dependent on the ability of the electronic circuit to measure time. For this reason the sharp leading edge of the applied pulse is used to gate the inverse time sweep.

In concluding their paper, the authors state: "The performance of the blood-pressure measuring systems described here remains to be evaluated."



CURRENT VIEWPOINTS THE HOUSTON CONFERENCE

Webb Associates, in an unpublished report to NASA dated January 1963, reported on a Conference held at the Manned Spacecraft Center, Houston, Texas, which was attended by a number of investigators active in the field of circulation research.

During the conference, methods of circulation measurement, which were under development at that time, were considered and compared with direct catheter methods and other circulatory instrumentation.

The techniques of pulse-wave-velocity (PWV) measurement and arterial tonometry were reviewed prominently, and the collective opinion of the conferees, as summarized by Webb Associates, is given here.

The conferees believed that measurement of PWV would not serve the same purpose as measurement of arterial pressure even though the relationship is close. The PWV is related to arterial distensibility—but not in a linear fashion (arterial distensibility varies with the level of arterial pressure and with such features as the ratio between artery-wall thickness and internal arterial diameter). There are two major objections to interpretation of PWV as arterial pres-

sure. First, the relationship is straightforward when a general change in arterial pressure occurs throughout the system. When specific changes in separate areas occur, however, the PWV in those areas varies independently. If the PWV is being measured in some other area, the relationship between it and arterial pressure is poor. Second, when a patient is under large doses of epinephrine, the ratio of artery-wall thickness to artery diameter can change from about 20:1 down to 4:1. Such an extreme change would radically alter the relationship between arterial pressure and PWV.

In this light the conferees concluded that a good deal of basic work had to be done to make PWV a useful cardiovascular tool. They believed that measurement of PWV could not now be used in place of arterial pressure measurement.

Arterial tonometry—the measurement of arterial pressure by means of force transducers located where a sizeable artery lies close to the skin—was discussed by the conferees. Devices have been developed independently by Stanford Research Institute (SRI) and the Engineering Research Laboratory (ERL) of the E. I. du Pont de Nemours and Company. Both are illustrated in detail in the recent Webb work, and diagrams of both are included as figure 12.

In the device designed by du Pont's Engineering Research Laboratory (ERL), a small metal block the size of a pencil has channels machined in it which allow the introduction and flow of a gas at constant rate (fig. 12, top). The gas can escape by squeezing past the end of a membrane-covered tubular chamber. When the membrane is pressed against an artery, the pulsations deflect the membrane and cause partial occlusion of the gas flow and a consequent pressure change within the chamber. Thus the chamber pressure—with flowing gas—varies with arterial pressure, and the device may then be calibrated.

Pressman and Newgard discuss this NASA-sponsored development of the Stanford Research Laboratories (SRI) in a paper describing methods of obtaining a continuous measurement of the arterial blood pressure by external means.

Initially, work was directed toward measurement of superficial effects of arterial distention. It soon became apparent, however, that skin displacement effects could not be related to blood pressure to the exclusion of other physiological influences such as skin tension and muscle tone. For example, certain drugs reduce the blood pressure, but the effect on the tissue tone of the patient is such that arterial distention increases. A displacement gage would thus register an increase instead of a decrease in blood pressure. Because of this limitation, work on this technique was dropped in favor of the direct force method described below.

To obtain a more accurate visualization of the nature of a blood pressure measuring system, it was decided to consider a mechanical model of the system characteristics. The model is based on the assumption that the deflections are so small as to make nonlinearities insignificant. Therefore, compressible and extensible tissue are represented as linear springs. The artery is assumed to rest on a firm base, to have elastic walls, and to be surrounded by uniform tissue. The transducer is assumed to have side structures that allow it to rest on the skin and a center structure that responds to arterial pressure.

The design of the direct force-measuring transducer is based on consideration of the mechanical model. Although a great variety of techniques are available for force measurement, all known methods involve the sensing of a displacement caused by the force to be measured. In the blood pressure transducer, the extremely low displacement complicates the selection of the basic sensing element. A strain gage was chosen for use in the first transducer designs. The availability of semiconductor strain gages permits the use of a low strain level but provides sufficient electrical output signal.

In the SRI device, the active element is a small arterial rider suspended on a stiff metal beam between two larger fixed plates. The mechanism is shown diagrammatically in the lower half of figure 12. Tiny deflections of the rider (in the order of 10 microinches) generate small signals from the strain gages on the beam. The deflection signal is calibrated first on an elastic tube, the pressure of which can be measured by a direct manometer. The device is then placed over the radial or the temporal artery, where it is carefully positioned so that the rider is centered over the artery. The device is then pressured down more and more firmly until a further increase in loading pressure causes no increase in the amplitude of the

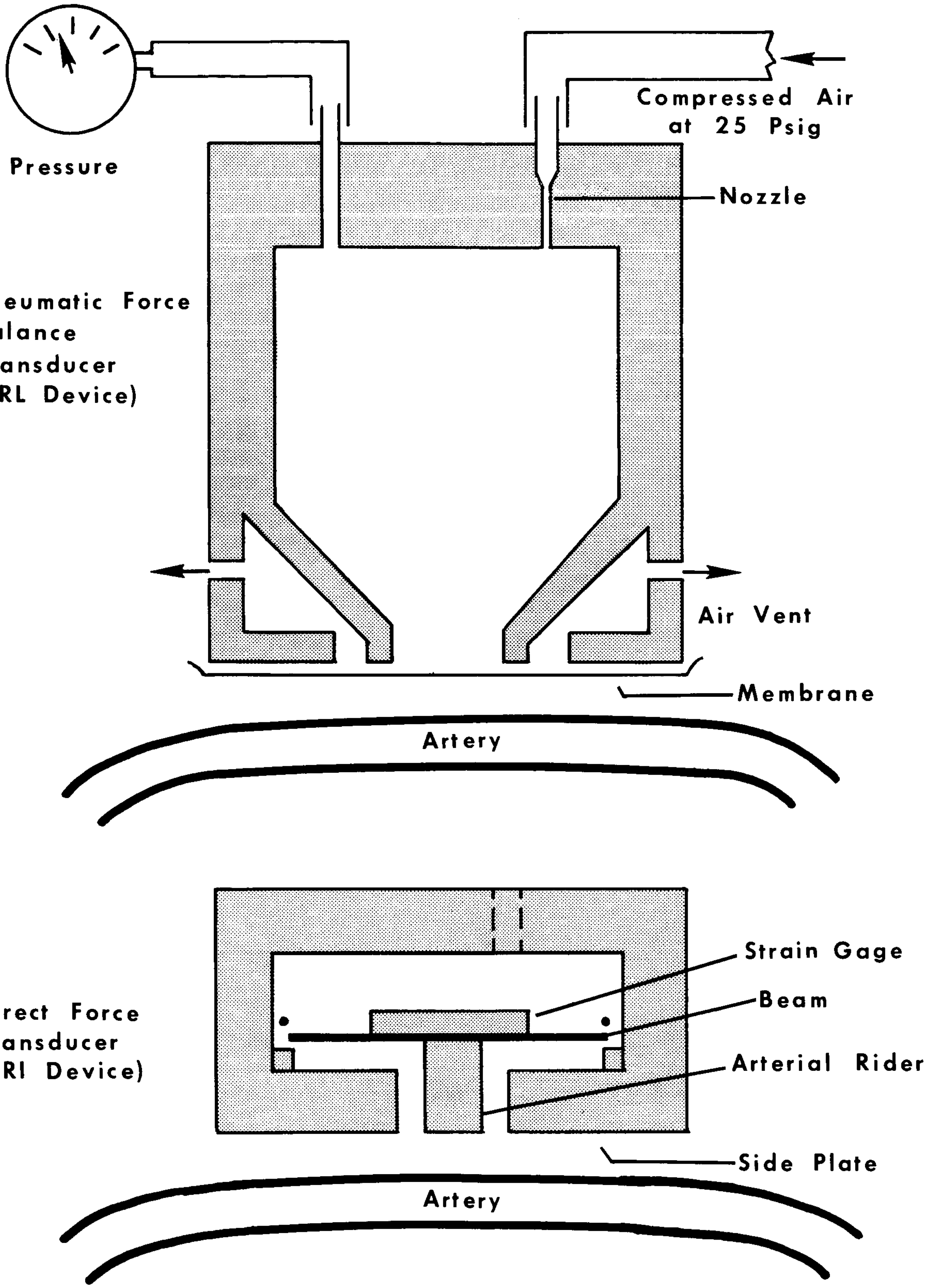


FIGURE 12.—Arterial tonometers. Top—du Pont device; bottom—SRI device (NASA-sponsored).

pressure pulses being detected. This plateau of pressure signal during increasing loading pressure is the main criterion for correct positioning.

In order to solve problems of temperature compensation in the strain gages and small signal size, SRI is considering changing from a deflection measurement with a strain gage to a dynamic force balance approach. This could be in the form of a sensor which would detect movement of the arterial rider from its zero position, the signal would generate energy which, when applied to a coil in a magnetic field, would restore the rider to its starting position. The null position could be maintained continuously by a fast-acting servo, and the varying energy needed to maintain the null position would be a function of the change in arterial pressure under the rider.

Despite the problems with small signal, position on the artery, and calibration, the conference attendants agreed that the arterial-tonometry approach was promising. Certainly there are forces in the skin and intervening tissue which must be overcome in order to achieve successful arterial tonometry. These forces, however, represent a fixed direct-current resistance in the system—at least over the short period of time required for measurement. The question still remains, of course, as to what relationship exists between air pressure in the chamber (or force applied to the arterial rider) and the blood pressure against the arterial wall.

In light of all the efforts which have been made in behalf of indirect measurement—and much difference of opinion on effectiveness and interpretation still exists—a significant opinion was advanced during the conference:

> . . . that with a comparable investment of time, energy, and funds, the direct-pressure measurement could perhaps be developed to a state of perfection in which the procedure would be essentially painless, relatively innocuous, and represent no limitation on the active subject.

BIBLIOGRAPHY

1. HALES, S.: Statical Essays: Vol. II, *Containing Haemastaticks.* London, 1731.
2. POISEUILLE, J. L. M.: Recherches sur la Force du Coeur Aortique. Paris, Univ. Thesis, 23, 1828.
3. LUDWIG, C.: Beiträge zur Kenntniss des Einflusses der Respirationsbewegungen auf den Blutlauf in Aortensysteme. Arch Anat Physiol Wissensch Med, *6*, 242, 1847.
4. VIERORDT, K.: Die Lehr vom Arterienpuls in Gesunden und Kranken Zuständen. Braunschweig, 1855.
5. MAREY, E. J.: Recherches sur le Pouls au Moyen d'un Nouvel Appareil Enregistreur (Sphygmographe). Gaz Méd de Paris, *225*, 236, 298, 1860.
6. VON BASCH, S.: Ueber die Volumetrische Bestimmung am Menschen. Wien Med Jahrb, 1876.
7. MAREY, E. J.: Pression et Vitesse du Sang. Paris, Physiol Exp, *2*, 307, 1876.
8. MAREY, E. J.: La Méthode Graphique dans les Sciences Expérimentales et Particulièrement en Physiologie et en Médecine. Paris, G. Masson, 1878.
9. MAREY, E. J.: Nouvelles Recherches Sur la Mesure Manometrique de la Pression du Sang Chez l'Homme, Physiol Exp, *4*, 225, 253, 1878–1879.
10. VON BASCH, S.: Ueber die Messung des Blutdrucks am Menschen. Z Klin Met, *2*, 79, 1881.
11. POTAIN, C.: Dù Sphygmomanometre et la Mesure de la Pression Arterielle Chez l'Homme. Arch Physiol Norm Path, *1*, 556, 1889.
12. POTAIN, C.: Determination Experimentale de la Valeur du Sphygmomanometre. Arch Physiol Path, *2*, 300, 1890.
13. POTAIN, C.: Faits Nouveaux Relatif a la Determination Experimentale de la Valeur du Sphygmomanometre. Arch Physiol Norm Path, *2*, 681, 1890.
14. MOSSO, A.: Sphygmomanometre pour Mesurer la Pression du Sang Chez l'Homme. Arch Ital Biol, *23*, 177, 1895.
15. HÜRTHLE, K.: Ueber eine Methode zur Registrierung des Arteriellen Blutdrucks beim Menschen. Dtsch Med Wschr, *22*, 574, 1896.
16. HILL, L., and BARNARD, H.: A Simple and Accurate Form of Sphygmomanometer or Arterial Pressure Gauge Contrived for Clinical Use. Brit. Med J, *2*, 904, 1897.
17. RIVA-ROCCI, S.: Un Nuovo Sfigmomanometro. Gazz Med di Torino, *47*, 981, 1001, 1896.
18. RIVA-ROCCI, S.: De la Mesuration de la Pression Arterielle en Clinique. Presse Méd, *22*, 307, 1899.
19. VON RECKLINGHAUSEN, H.: Ueber Blutdruckmessung beim Menschen. Arch Exper Path U Pharmakol, *46*, 78, 1901.
20. BAYLISS, W. M.: On the Local Reactions of the Arterial Wall to Changes of Internal Pressure. J Physiol, *28*, 220, 1902.
21. ERLANGER, J.: A New Instrument for Determining Systolic and Diastolic Blood Pressure in Man. Am J Physiol, *6*, 22, 1902.
22. POTAIN, P. C.: La Pression Arterielle de l'Homme a l'Etat Normale et Pathologique. Paris, G. Masson, 190 .
23. VASCHIDE, N., and LAHY, J. M.: La Technique de la Mésure de la Pression Sanquine Particulièrement Chez l'Homme. Arch Gen de Méd, *2*, 349, 480, 602, 1902.
24. FRANK, O.: Kritik der Elastischen Manometer. Z Biol, *44*, 445–613, 1903.
25. STANTON, W. B.: A Practical Clinical Method for Determining Blood Pressure in Man, with a Discussion of the Methods Hitherto Employed. Univ Pennsylvania M Bull, *15*, 466, 1903.
26. ERLANGER, J.: A Study of the Errors Involved in the Determination of the Blood Pressure in Man, Together with a Demonstration of the Improvements in the Sphygmomanometer Suggested Thereby. Am J of Physiol, *10*, 14, 1903–1904.
27. ERLANGER, J., and HOOKER, D. R.: An Experimental Study of Blood Pressure and of Pulse Pressure in Man. Johns Hopkins Hosp Rep, *12*, 145, 1903–1904.
28. ERLANGER, J.: A New Instrument for Determining the Minimum and Maximum Blood Pressures in Man. Johns Hopkins Hosp Rep, *12*, 53, 1904.

29. JANEWAY, T. C.: The Clinical Study of Blood Pressure. New York, D. Appleton & Co., 1904.
30. KOROTKOFF, N. S.: A Contribution to the Problem of Methods for the Determination of the Blood Pressure. Rep Imper Milit-Med Acad, St. Petersburg, *11*, 365, 1905.
31. MARTIN, C. J.: The Determination of Arterial Blood Pressure in Clinical Practice. Brit Med J, *1*, 865, 1905.
32. BAYLISS, W. M.: The Excitation of Vaso-Dilator Nerve-Fibers in Depressor Reflexes. J Physiol, *37*, 264, 1908.
33. KRILOV, D. D.: On Measuring the Blood Pressure by the Sound Method of Dr. N. S. Korotkoff. Bull Imper Milit-Med Acad, *13*, 113, 221, 1908.
34. JANEWAY, T. C.: The Influence of the Soft Tissues of the Arm on Clinical Blood-Pressure Determinations. Arch Int Med, *3*, 474, 1909.
35. PACHON, V.: Oscillomètre Sphygmomètrique a Grande Sensibilitē et à Sensibilitē Constante. Compt Rend Soc de Biol, *66*, 776, 1909.
36. GITTINGS, J. C.: Auscultatory Blood-Pressure Determinations. Arch Int Med, *6*, 196, 1910.
37. HILL, L.: The Measurement of Systolic Blood Pressure in Man. Heart, *1*, 73, 1909–10.
38. JANEWAY, T. C., and PARK, E. A.: An Experimental Study of the Resistance to Compression of the Arterial Wall. Arch Int Med, *6*, 586, 1910.
39. HILL, L., and ROWLANDS, R. A.: Systolic Blood Pressure: (1) In Change of Posture; (2) In Cases of Aortic Regurgitation. Heart, *3*, 219, 1911–12.
40. MACWILLIAM, J. A., and KESSON, J. E.: The Estimation of Systolic Blood Pressure in Man with Special Reference to the Influence of the Arterial Wall. Heart, *4*, 279, 1912–13.
41. WEYSSE, A. W., and LUTZ, B. R.: A Comparison of the Auscultatory Blood Pressure Phenomenon in Man with the Tracing of the Erlanger Sphygmomanometer. Am J Physiol, *32*, 427, 1913.
42. JANEWAY, T. C.: Important Contributions to Clinical Medicine During the Past 30 Years from the Study of Human Blood Pressure. Bull Johns Hopkins Hosp, *26*, 341, 1915.
43. BARRINGER, T. B., Jr.: The Circulatory Reaction to Graduated Work as a Test of the Heart's Functional Capacity. Arch Int Med, *17*, 363, 1916.
44. BROOKS, C., and LUCKHARDT, A. B.: The Chief Physical Mechanisms Concerned in Clinical Methods of Measuring Blood Pressure. Am J Physiol, *40*, 49, 1916.
45. ERLANGER, J.: Studies in Blood-Pressure Estimations by Indirect Methods: the Mechanism of the Oscillatory Criteria. Am J Physiol, *39*, 401, 1916.
46. ERLANGER, J.: Studies in Blood-Pressure Estimation by Indirect Methods; the Mechanism of the Compression Sounds of Korotkoff. Am J Physiol, *40*, 82, 1916.
47. ERLANGER, J.: The Preanacrotic Phenomenon and Its Relation to the Arterial Compression Sounds of Korotkoff; A Demonstration. Am J Physiol, *45*, 565, 1918.
48. ELLIS, M. M.: Pulse-Rate and Blood-Pressure Responses of Men to Passive Postural Changes. Am J Med Sc, *161*, 568, 1921.
49. ADDIS, T.: Blood Pressure and Pulse Rate Levels; Levels Under Basal and Daytime Conditions. Arch Int Med, *29*, 539, 1922.
50. MARTIN, K. A., and WHITE, H. L.: Blood Pressure Responses to Suprasystolic Compression of Tissues. J Missouri M A, *19*, 196, 1922.
51. SCHNEIDER, E. C., and TRUESDELL, D.: Statistical Study of Pulse Rate and Arterial Blood Pressures in Recumbency, Standing, and after a Standard Exercise. Am J Physiol, *61*, 429, 1922.
52. MORTENSEN, M. A.: Blood-Pressure Reactions to Passive Postural Changes an Index to Myocardial Efficiency. Am J Med Sc, *165*, 667, 1923.
53. WIGGERS, C. J.: Modern Aspects of the Circulation in Health and Disease. Ed. 2, Philadelphia, Lea & Febiger, 1923.
54. BAZETT, H. C.: Factors in Causation of Differential Blood Pressure. Am J Physiol, *70*, 550, 1924.
55. FABER, A., and MACKEPRANG, E.: Blood Pressure in 1,000 Persons, Aged 20–25; Comparison Between Riva-Rocci and Sahli Sphygmomanometers. Compt Rend Soc de Biol, *91*, 781, 1924.
56. BURDICK, W., CLARKE, N., GARLICHS, R., PRIESTLEY, J., and RICHARDS, D.: Differences in Blood Pressure in Arm and Leg in Normal Subjects. Am J Physiol, *72*, 169, 1925.
57. DIEHL, H. S., and SUTHERLAND, K. H.: Systolic Blood Pressures in Young Men, Including Special Study of Those with Hypertension. Arch Int Med, *36*, 151, 1925.
58. MACWILLIAM, J. A.: Blood Pressures in Man Under Normal and Pathological Conditions. Physiol Rev, *5*, 303, 1925.
59. ALVAREZ, W. C., MCCALLA, R. L., and ZIMMERMANN, A.: Hypertension and Constipation; Statistical Inquiry. Arch Int Med, *38*, 158, 1926.
60. BRAMWELL, J. C. and HICKSON, S. K.: Relation of Pulse Form to Sound Production in Arteries; Optical Phonoarteriograms. Heart, *13*, 129, 1926.

61. Korns, H. M.: Nature and Time Relations of Compression Sounds of Korotkov in Man. Am J Physiol, *76*, 247, 1926.
62. Norris, G. W., Bazett, H. C., and McMillan, T. M.: Blood Pressure; Its Clinical Applications. Lea & Febiger, Philadelphia, 1927.
63. Turner, A. H.: Adjustment of Heart Rate and Arterial Pressure in Healthy Young Women During Prolonged Standing. Am J Physiol, *81*, 197, 1927.
64. Wilson, J. L., Eaton, H. N., and Henrickson, H. B.: Use and Testing of Sphygmomanometers. U.S. Government Printing Office, Washington, D. C., 1927.
65. Diehl, H. S.: Variability of Blood Pressure; Morning and Evening Studies. Arch Int Med, *43*, 835, 1929.
66. Diehl, H. S., and Lees, H. D.: The Variability of Blood Pressure; A Study of Systolic Pressure at Five-Minute Intervals. Arch Int Med, *44*, 229, 1929.
67. Forssmann, W.: Die Sondierung des Rechten Herzens. Klin Wschr, *8*, 2085, 2287, 1929.
68. Brim, C. J.: The Story of Blood Pressure. Med Life, *37*, 60, 1930.
69. Davis, H. J.: Notes on Blood Pressure in Old Age. Human Biol, *2*, 264, 1930.
70. Christ, D. G.: Variations in Pulse and Blood Pressure with Change of Posture. Proc Staff Meet, Mayo Clin, *5*, 272, 1930.
71. Dameshek, W., and Loman, J.: Direct Intra-arterial Blood-Pressure Readings in Man. Am J Physiol, *101*, 140 1932.
72. Hines, E. A., Jr., and Brown, G. E.: A Standard Stimulus for Measuring Vasomotor Reactions: Its Application in the Study of Hypertension. Proc Staff Meet, Mayo Clin, *7*, 332, 1932.
73. von Bonsdorff, B.: Zur Methodik der Blutdrukmessung, mit Besonderer Berücksichtigung der Registrierung Absoluter Sphygmogramme beim Menschen. Acta Med Scandinav Supp, *51*, 1, 1932.
74. Wetherby, M.: Comparison of Blood Pressure in Men and Women; Statistical Study of 5,540 Individuals. Ann Int Med, *6*, 754, 1932.
75. Brams, W. A., Katz, L. N., and Kohn, L.: Effect of Abdominal Distention and Release on Blood Pressures in Arteries and Viens. Am J Physiol, *104*, 120, 1933.
76. Briggs, J. F., and Oerting, H.: Vasomotor Response of Normal and Hypertensive Individuals to Thermal Stimulus (Cold). Minnesota Med, *16*, 481, 1933.
77. Diehl, H. S., and Hesdorffer, M. B.: Changes in Blood Pressure of Young Men over a Seven-Year Period. Arch Int Med, *52*, 948, 1933.
78. Garner, J. R.: Blood Pressure as Affected by Improper Posture. Int J Med & Surg, *46*, 535, 1933.
79. Hines, E. A., Jr., and Brown, G. E.: A Standard Test for Measuring the Variability of Blood Pressure: Its Significance as an Index of the Prehypertensive State. Ann Int Med., *7*, 209, 1933.
80. Korns, H. M., and Guinand, P. H.: Inequality of Blood Pressure in the Brachial Arteries, with Especial Reference to Disease of the Arch of the Aorta. J. Clin Invest, *12*, 145, 1933.
81. MacWilliam, J. A.: Postural Effects of Heart Rate and Blood Pressure. Quart J Exper Physiol, *23*, 1, 1933.
82. Hamilton, W. F., Brewer, G., and Brotman, I.: Pressure Pulse Contours in Intact Animal; Analytical Description of New High-Frequency Hypodermic Manometer with Illustrative Curves of Simultaneous Arterial and Intracardiac Pressures. Am J Physiol, *107*, 427, 1934.
83. Morris, D. P.: Effects of Emotional Excitement on Pulse, Blood Pressure, and Blood Sugar of Normal Human Beings. Yale J Biol Med, *7*, 401, 1935.
84. Hamilton, W. F., Woodbury, R. A., and Harper, H. T., jr.: Physiological Relationships Between Intrathoracic, Intraspinal and Arterial Pressures. J A M A, *107*, 853, 1936.
85. Hines, E. A., Jr., and Brown, G. E.: The Cold Pressor Test for Measuring the Reactibility of the Blood Pressure: Data Concerning 571 Normal and Hypertensive Subjects. Am Heart J *11*, 1, 1936.
86. Loman, J., Dameshek, W., Myerson, A., and Goldman, D.: Effect of Alterations in Posture on the Intra-arterial Blood Pressure in Man; Pressure in Carotid, Brachial and Femoral Arteries in Normal Subjects. Arch Neurol Psychiat, *35*, 1216, 1936.
87. Pickering, G. W., and Kissin, M.: The Effects of Adrenaline and of Cold on the Blood Pressure in Human Hypertension. Clin Sc, *2*, 201, 1936.
88. Hines, E. A., Jr.: Reaction of the Blood Pressure of 400 School Children to a Standard Stimulus. J A M A, *108*, 1249, 1937.
89. Lutterloh, C. H.: Clinical Significance of Effects of Posture on Blood Pressure; Postural Test as Means of Classifying Hypotension. Am J M Sc, *193*, 87, 1937.

90. Wald, H., Guernsey, M., and Scott, F. H.: Some Effects of Alteration of Posture on Arterial Blood Pressure. Am Heart J, *14*, 319, 1937.
91. Alam, M., and Smirk, F. H.: Observations in Man Concerning Effects of Different Types of Sensory Stimulation Upon Blood Pressure. Clin Sc, *3*, 253, 1938.
92. Alam, M., and Smirk, F. H.: Blood Pressure Raising Reflexes in Health, Essential Hypertension, and Renal Hypertension. Clin Sc, *3*, 259, 1938.
93. Ayman, D., and Goldshine, A. D.: Cold as Standard Stimulus of Blood Pressure; Study of Normal and Hypertensive Subjects. New England J Med, *219*, 650, 1938.
94. Dieckmann, W. J., Michel, H. L., and Woodruff, P. W.: The Cold Pressor Test in Pregnancy. Am J Obst Gynec, *36*, 408, 1938.
95. Lewis, W. H., Jr.: Changes With Age in Blood Pressures in Adult Men. Am J Physiol, *122*, 491, 1938.
96. Ogden, E., and Shock, N. W.: Rate of Stabilization of Systolic Blood Pressure Following Adoption of Supine Posture. Quart J Exper Physiol, *28*, 341, 1938.
97. Alexander, F.: Emotional Factors in Essential Hypertension; Presentation of Tentative Hypothesis. Psychosom Med, *1*, 173, 1939.
98. Ayman, D., and Goldshine, A. D.: Breath-Holding Test; Simple Standard Stimulus of Pressure. Arch Int Med, *63*, 899, 1939.
99. Robinson, S. C., and Brucer, M.: Range of Normal Blood Pressure; Statistical and Clinical Study of 11,383 Persons. Arch Int Med, *64*, 409, 1939.
100. Roess, Louis C.: A Condenser-Type High-Speed Engine Indicator. Rev Sc Inst, 183, June, 1940.
101. Ayman, D., and Goldshine, A. D.: Blood Pressure Determinations in Patients with Essential Hypertension; Difference Between Clinic and Home Readings Before Treatment. Am J M Sc, *200*, 465, 1940.
102. Berry, M. R., Jr., Horton, B. T., and MacLean, A. R.: Importance of Studying Postural Responses of Blood Pressure and Heart Rate With Note on Method of Taking Blood Pressure in Erect Posture. M Clin North America, *24*, 1095, 1940.
103. Berry, M. R., Jr.: Vascular Clinics; Mechanism and Prevention of Impairment of Auscultatory Sounds During Determination of Blood Pressure of Standing Patients. Proc Staff Meet, Mayo Clin, *15*, 699, 1940.
104. Erlanger, J.: Relation of Longitudinal Tension of Artery to Preanacrotic (breaker) Phenomenon. Am Heart J, *19*, 398, 1940.
105. Hampel, A., Elektrisches Transmissionsmanometer auf der Grundlage elektrischer Widerstandsänderungen des Wismuts in Magnetfeld. Pflüg Arch ges Physiol, *244*, 171–175, 1940.
106. Hines, E. A., Jr.: Range of Normal Blood Pressure and Subsequent Development of Hypertension; Follow-up Study of 1,522 Patients. J A M A, *115*, 271, 1940.
107. Hines, E. A., Jr.: The Significance of Vascular Hyperreaction as Measured by the Cold-pressor Test. Am Heart J, *19*, 408, 1940.
108. Thacker, E. A.: A Comparative Study of Normal and Abnormal Blood Pressures Among University Students, Including the Cold-pressor Test. Am Heart J, *20*, 89, 1940.
109. von Recklinghausen, H.: Blutdruckmessung and Kreislauf in den Arterien des Menschen. Theodore Steinkopff, Dresden and Leipzig, 1940.
110. Treloar, A. E.: Normal Blood Pressure. Arch Int Med, *66*, 848, 1940.
111. Berry, M.: Vascular Clinics; Influence of Position of Arm and Body on Blood Pressure Determined by Auscultation. Proc Staff Meet, Mayo Clin, *16*, 29 (1941).
112. Feldt, R. H., and Wenstrand, D. E. W.: Cold-Pressor and Breath-Holding Test; Analysis of Results in 200 Subjects. Arch Int Med, *67*, 1157, 1941.
113. Lewis, W. H., Jr.: Evolution of Clinical Sphygmomanometry. Bull New York Acad Med, *17*, 871, 1941.
114. Miller, I.: Blood Pressure Studies in Aged. New York State J Med, *41*, 1631, 1941.
115. Morris, D. P.: Blood Pressure and Pulse Changes in Normal Individuals Under Emotional Stress; Their Relationship to Emotional Instability. Psychosom Med, *3*, 389, 1941.
116. The Accuracy of Clinical Determination of Arterial Pressure. Tr A Am Physicians, *56*, 222, 1941.
117. Ragan, C., and Bordley, J., III: Accuracy of Clinical Measurements of Arterial Blood Pressure, With a Note on the Auscultatory Gap. Bull Johns Hopkins Hosp, *69*, 504, 1941.
118. Richards, D. W., Jr., Cournand, A., Darling, R. C., and Gillespie, W. H.: Pressures in the Right Auricle in Man, in Normal Subjects, and in Patients with Congestive Heart Failure. Trans Assoc Am Physicians, *56*, 218, 1941.

119. Wolf, Stewart and Hardy, J. D.: Studies on Pain. Observations on Pain Due to Local Cooling and on Factors Involved in the "Cold-Pressor" Test. J Clin Invest, *20*, 521, 1941.
120. Lilly, John C.: The Electrical Capacitance Diaphragm Manometer. Rev Sci Inst, 34, January, 1942.
121. Feldt, R. H., and Wenstrand, D. E. W.: Cold-Pressor Test in Subjects with Normal Blood Pressure; Report of Observations on 350 Subjects, with Special Reference to Family History. Am Heart J, *23*, 766, 1942.
122. Master, A. M., and Dack, S.: Hypertension in Workers Over 40 Years of Age; Preliminary Report. Indust Med, *11*, 145, 1942.
123. Neumann, C., Cohn, A. E., and Burch, G. E.: Study of Influence of Character of Examining Room on Peripheral Blood Vessels of Normal, Hypertensive, and Senile Subjects. J Clin Invest, *21*, 651, 1942.
124. Steele, J. M.: Comparison of Simultaneous Indirect (Auscultatory) and Direct (Intra-arterial) Measurements of Arterial Pressure in Man. J Mt Sinai Hosp, *8*, 1042, 1942.
125. Gilson, W. E.: Application of Electronics to Physiology. Elec, *16*, 86–88, January, 1943.
126. Gilson, W. E.: Photoelectric Manometer (Improved Design). Elec, *16*, 112, 140, April, 1943.
127. Frommer, Joseph C.: Detecting Small Mechanical Movements. Elec, July, 1943.
128. Alam, G. M., and Smirk, F. H.: Casual and Basal Blood Pressures in British and Egyptian Men. Brit Heart J, *5*, 152, 1943.
129. Alam, G. M., and Smirk, F. H.: Casual and Basal Blood Pressures in Essential Hypertension. Brit Heart J, *5*, 156, 1943.
130. Gell, C. F.: Postural Changes in Standing Blood Pressure Affecting Aviation Circulatory Efficiency Rating. U S Nav M Bull, *41*, 48, 1943.
131. Master, A. M., Marks, H. H., and Dack, S.: Hypertension in People Over 40. J A M A, *121*, 1251, 1943.
132. Potter, E. V.: An Electrical Transducer Circuit for Use with Capacity Pickup Devices. Rev Sci Inst, 130, May, 1943.
133. Russek, H. I.: Blood Pressure in Aged; Study of 1,000 Elderly Male Subjects. Am Heart J, *26*, 11 (1943); Correction, *26*, 289, 1943.
134. Wendkos, M. H., and Rossman, P. L.: Normal Blood Pressure in Lower Extremity. Am Heart J, *26*, 623, 1943.
135. Wetterer, E.: Eine Neue Manometrische Sonde Mit Elektrischer Transmission. Z Biol, *101*, 332–350, 1943.
136. Clarke, James G.: Differentiating and Integrating Circuits. Elec, 138, November, 1944.
137. Cournand, A., Lauson, H. D., Bloomfield, R. A., Breed, E. S., and Baldwin, E. de F.: "Recording of Right Heart Pressures in Man." Proc Exp Biol, *55*, 34, New York, 1944.
138. Gambill, E. E.: Diurnal and Seasonal Variation of Blood Pressure in Arm and Thigh of Man. Proc Staff Meet, Mayo Clin, *19*, 155, 1944.
139. Hamilton, W. F.: Patterns of Arterial Pressure Pulse. Am J Physiol, *141*, 235, 1944.
140. Kotte, J. H., Iglauer, A., and McGuire, J.: Measurements of Arterial Blood Pressure in Arm and Leg; Comparison of Sphygmomanometric and Direct Intra-arterial Pressures, with Special Attention to Their Relationship in Aortic Regurgitation. Am Heart J, *28*, 476, 1944.
141. Salit, E. P., and Tuttle, W. W.: Variability of Heart Rate and Blood Pressure in Selected Groups of College and High School Students. J. Lab & Clin Med, *29*, 1139, 1944.
142. Smirk, F. H.: Casual and Basal Blood Pressures; Their Relationship to Supplemental Pressure with Note on Statistical Implications. Brit Heart J, *6*, 176, 1944.
143. Bruce, M. B., Martin, R. T., and Smirk, F. H.: Effect of Initial Level of Blood Pressure Upon Response of Human Subject to Blood Pressure Raising Reflexes. J. Physiol, *103*, 412, 1945.
144. Curtis, W. F.: Measurement of Stresses in Rotating Shafts. Elec, 114, July, 1945.
145. Russek, H. I., and Zohman, B. L.: Influence of Age Upon Blood-Pressure Response to Cold-Pressor Test. Am Heart J, *29*, 113, 1945.
146. Bloomfield, R. A., Lauson, H. D., Cournand, A., Breed, E. S., and Richards, D. W., Jr.: Recording of Right Heart Pressures in Normal Subjects and in Patients with Chronic Pulmonary Disease and Various Types of Cardiocirculatory Disease, J Clin Invest, *25*, 639, 1946.
147. Lauson, H. D., Bloomfield, R. A., and Cournand, A.: Influence of Respiration on Circulation in Man, with Special Reference to Pressures in Right Auricle, Right Ventricle, Femoral Artery and Peripheral Veins. Am J Med, *1*, 315, 1946.
148. Russek, H. I., Rath, M. M., Zohman, B. L., and Miller, I.: Influence of Age on Blood Pressure; Study of 5,331 White Male Subjects. Am Heart J, *32*, 468, 1946.
149. Stein, I.: Effect of Change of Position of Arm Upon Blood Pressure. Am Heart J, *31*, 477, 1946.

150. Motley, H. L., Cournand, A., Werko, L., Dresdale, D., Himmelstein, A., and Richards, D. W.: Intravascular and Intracardiac Pressure Recording in Man: Electrical Apparatus Compared with the Hamilton Manometer. Proc Soc Exp Biol, *64*, 241–244, February, 1947.
151. Roberts, C.: Carrier-Type Amplifier for Electric Gauges. Elec 92, May, 1947.
152. Lilly, J. C., Legallais, V. and Cherry, R.: A Variable Capacitor for Measurements of Pressure and Mechanical Displacements; a Theoretical Analysis and Its Experimental Evaluation. J Appl Phys, 513, July, 1947.
153. Boynton, R. E., and Todd, R. L.: Blood Pressure Readings of 75,258 University Students. Arch Int Med, *80*, 454, 1947.
154. Conant, J. B.: On Understanding Science. An Historical Approach. New Haven, Conn., 1947.
155. Goldenberg, M., Snyder, C. H., and Aranow, H., Jr.: New Test for Hypertension Due to Circulating Epinephrine. J A M A, *135*, 971, 1947.
156. Krieger, V. I., and Weiden, S.: The Value of the Cold-Pressor Test in the Prediction of Hypertension and Toxaemia in Pregnancy. M J Australia, *1*, 417, 1947.
157. LaDue, J. S., Murison, P. J., and Pack, G. T.: Use of Tetraethylammonium Bromide as Diagnostic Test for Pheochromocytoma. Proc Am Fed Clin Res, *3*, 67, 1946.
158. Lambert, E. H., and Wood, E. H.: The Use of Resistance Wire, Strain Gauge Manometer to Measure Intraarterial Pressure. Proc Soc Exper Biol & Med, *64*, 186, 1947.
159. Remington, J. W., Noback, C. R., Hamilton, W. F., and Gold, J. J.: Volume Elasticity Characteristics of the Human Aorta and Prediction of the Stroke Volume From the Pressure Pulse. Am J Physiol, *153*, 298–308, May, 1948.
160. Espy, D.: Design Curves for Parallel-T Networks. Elec, 114, July, 1948.
161. Keegan, A. G., and McIntosh, R. L.: Strain-Sensitive Resistance-Wire Manometer. Rev Sci Inst, 502, August, 1948.
162. Matheson, H., and Eden, M.: A Highly Sensitive Differential Manometer. Rev Sci Inst, 502, August, 1948.
163. Bierman, H. R.: Device for Measuring Physiological Pressure Phenomena Using the Bonded Electrical Wire Resistance Strain Gauge. Rev Sci Inst, 707, October, 1948.
164. Buck, W. E., and Barkas, W. H.: Dynamic Pressure Measurements by Optical Interference. Rev Sci Inst, 678, October, 1948.
165. Currens, J. H.: Comparison of Blood Pressure in Lying and Standing Positions: Study of 500 Men and 500 Women. Am Heart J, *35*, 646, 1948.
166. Green, R. S., Iglauer, A., and McGuire, J.: Alterations of Radial or Brachial Intra-arterial Blood Pressure and of Electrocardiogram Induced by Tilting. J Lab & Clin Med, *33*, 951, 1948.
167. Perera, G. A.: Diagnosis and Natural History of Hypertensive Vascular Disease. Am J Med, *4*, 416, 1948.
168. White, G. E.: Liquid Filled Pressure Gage Systems. Statham Lab Instr Notes No. 7, January–February, 1949.
169. Noble, F. W.: A Capacitance Diaphragm Manometer for Blood-Pressure Recording. Macy Foundation Conference on Factors Regulating Blood Pressure, May 5, 1949.
170. Schafer, P. W., and Shirer, H. W.: An Impedance Gauging System for Measurement of Biologic Pressure Variables. Surgery, *26*, 446–451, September, 1949.
171. Hansen, A. T.: Pressure Measurement in the Human Organism. Acta Physiol Scand, *19* (suppl. 68), 1949.
172. Thomson, A. E., and Doupe, J.: Causes of Error in Auscultatory Blood Pressure Measurements. Rev Canad de Biol, *8*, 337, 1949.
173. Wood, E. H., Lambert, E., and Burchell, H. B.: The Application of a Strain Gauge Manometer, a Modified Ear Oximeter and a Whole Blood Cuvette Oximeter to the Technic of Cardiac Catheterization. J Clin Invest, *28*, 819, 1949.
174. Gauer, O. H., and Gienapp, E.: A Miniature Pressure Recording Device. Science, *112*, 404–405, October 6, 1950.
175. Master, A. M., Dublin, L. I., and Marks, H. H.: Normal Blood-Pressure Range and its Clinical Implications. J A M A, *143*, 1464, 1950.
176. Isaacson, I., and Jones, R. E.: An Electromagnetic Hydraulic Transducer for Studying Response Characteristics of Manometer Systems to Square Wave and Sine Wave Pressure Variations of Variable Frequency. Am J Physiol, *163*, 722–723, 1950.
177. Lambert, E. H.: Strain Gages: Resistance Wire in Medical Physics. *2*, O. Glasser, Ed., Year Book Publishers, Chicago, Ill., 1090–1098, 1950.
178. Wood, E. H.: Oximetry. Medical Physics (O. Glasser, Ed.), *2*, Year Book Publishers, Chicago, Ill., 671–672, 1950.

179. Wood, E. H., Knutson, J. R. B., and Taylor, B. E.: Measurement of Blood Content and Arterial Blood Pressure in Human Ear. Proc Staff Meet, Mayo Clin, *25*, 398, July 5, 1950.
180. Ellis, E. J., Gauer, O. H., and Wood, E. H.: An Intracardiac Monometer: Its Evaluation and Application. Cir Res, *3*, 390–398, March, 1951.
181. Bordley, J., III, Connor, C. A. R., Hamilton, W. F., Kerr, W. J., and Wiggers, C. J.: Recommendations for Human Blood Pressure Determinations by Sphygmomanometers. Circulation, *4*, 503-509, 1951.
182. Hines, E. A., Jr.: Vascular Reactivity and Hypertensive Disease, in Hypertension . . . A Symposium, Bell, E. T., Ed., Minneapolis, University of Minnesota Press, 331–341, 1951.
183. Committee to Revise Standardization of High Blood Pressure Readings: Recommendations for Human Blood Pressure Determinations by Sphygmomanometers. Amer Heart Assoc, New York, 1951.
184. Goldring, D., and Wohltman, H.: Flush Method for Blood Pressure Determinations in Newborn Infants. J Pediat, *40*, 285, 1952.
185. Master, A. M., Garfield, C. I., and Walters, M. B.: Normal Blood Pressure and Hypertension: New Definitions. Lea & Febiger, Philadelphia, 1952.
186. Wetterer, E., and Pieper, H.: Eine Neue Manometrische Sonde mit Elektrischer Transmission, II Mitteilung. Z Biol, *105*, 49–65, 1952.
187. Parnell, J., Beckman, E. L., and Peterson, L. H.: The Evaluation of Pressure Transducer Systems. US Nav Develop Ctr, Rept No NADC–MA–5206, January, 1953.
188. Roberts, L. N., Smiley, J. R., and Manning, G. W.: A Comparison of Direct and Indirect Blood-Pressure Determinations. Circulation Res, *8*, 232–242, August, 1953.
189. Hamilton, W. F.: Lewis A. Connor Memorial Lecture—Physiology of Cardiac Output. Circulation, *8*, 527, 1953.
190. Noble, F. W.: "Electrical Methods of Blood Pressure Recording," Charles C. Thomas Publishers, Springfield, Ill., 1953.
191. Rodbard, S.: Significance of Intermediate Korotkoff Sounds. Circulation, *8*, 600, (1953).
192. Wetterer, E., and Pieper, H.: Über die Gesamtelastizität des Arteriellen Windkessels und ein Experimentelles Verfahren zu ihrer Bestimmung am Lebenden Tier. Z Biol, *106*, 23–57, 1953.
193. Freis, E. D.: Discrepancy Between Home and Office Recordings of Blood Pressure in Patients Under Treatment with Pentapyrrolidinium: Importance of Home Recordings in Adjusting Dosages. M Ann, District of Columbia, *23*, *363*, 1954.
194. Hamilton, M., Pickering, G. W., Roberts, J. A. F., and Sowry, G. S. C.: Aetiology of Essential Hypertension: Arterial Pressure in General Population. Clin Sc, *13*, 11, 1954.
195. Pickering, G. W.: High Blood Pressure. Grune & Stratton, Inc., New York (1954).
196. Pickering, G. W., Roberts, J. A. F., and Sowry, G. S. C.: Aetiology of Essential Hypertension; Effect of Correcting for Arm Circumference on Growth Rate of Arterial Pressure with Age. Clin Sc, *13*, 267, 1954.
197. Schroeder, H. A.: Hypertension, Method of Treatment in Current Therapy, (Conn, H. F., and Others, Ed.), 1954, Latest Approved Methods of Treatment for the Practicing Physician, W. B. Saunders Co., Philadelphia, 1954.
198. von Euler, U. S., Hellner, S., and Purkhold, A.: Excretion of Noradrenaline in Urine in Hypertension. Scandinav J Clin & Lab Invest, *6*, 54, (1954).
199. Bromberger-Barnea, B., Maaske, C. A., and Greenwood, I., Jr.: A Miniature Pressure Transducer for Introvascular and Intracardiac Use. Cir Res, *12*, 685, October, 1955.
200. Green, J. H.: Blood-Pressure "Follower" for Continuous Blood Pressure Recording in Man, J Physiol, *130*, 37P–38P, November, 1955.
201. Corcoran, A. C., Dustan, H. P., and Page, I. H.: Evaluation of Antihypertensive Procedures, with Particular Reference to Their Effects on Blood Pressure. Ann Int Med, *43*, 1161, 1955.
202. Gunteroth, W. G., and Nadas, A. S.: Symposium on Laboratory Tests and Special Procedures; Blood Pressure Measurements in Infants and Children. Pediat Clin North America, *2*, 257, 1955.
203. Reinhold, J., and Pym, M.: Determination of Blood Pressure in Infants by Flush Method. Arch Dis Childhood, *30*, 127, 1955.
204. Wood, J. E., Litter, J., and Wilkins, R. W.: Mechanism of Limb Segment Reactive Hyperemia in Man. Cir Res, *3*, 581, 1955.
205. Nuessle, W. F.: The Importance of a Tight Blood Pressure Cuff. Am Heart J, *52*, 905, 1956.
206. Wiggers, C. J.: Dynamic Reactions Induced by Compression of an Artery. Cir Res, *4*, 4, 1956.
207. Fry, D. L., Noble, F. W., and Mallos, A. J.: An Electric Device for Instantaneous and Continuous Computation of Aortic Blood Velocity. Cir Res, *5*, 75–78, January, 1957.

208. WARNER, H. R.: A Study of the Mechanism of Pressure Wave Distortion by Arterial Walls Using an Electrical Analog. Cir Res, *5*, 79–84, January, 1957.
209. CURRENS, J. H., BROWNELL, G. L., and ARONOW, S.: An Automatic Blood Pressure Recording Machine. New Eng J Med, *256*, 780–784, April 25, 1957.
210. NOBLE, F. W.: The Sonic Valve Pressure Gauge. IRE Trans Med Elec, *ME-8*, 38–44, July, 1957.
211. BROTMACHER, L.: Evaluation of Derivation of Cardiac Output from Blood Pressure Measurements. Cir Res, *5*, 589–593, November, 1957.
212. HEYMAN, A., KARP, H. R., and BLOOR, B. M.: Determination of Retinal Artery Pressures in Diagnosis of Carotid Artery Occlusion. Neurology, *7*, 97–104, 1957.
213. RODBARD, S., RUBINSTEIN, H. M., and ROSENBLUM, S.: Arrival Time and Calibrated Contour of the Pulse Wave, Determined Indirectly from Recordings of Arterial Compression Sounds. Am Heart J, *53*, 205, 1957.
214. ABRAHAMS, V. C., and HILTON, S. M.: Active Muscle Vasodilation and Its Relation to the "Flight and Fight Reactions" in the Conscious Animal. J Physiol, *140*, 16P, 1958.
215. GREER, J. R.: A Sensitive Defocusing Photo-Electric Pressure Transducer. Elec Eng, *30*, 436–439, July, 1958.
216. McKUSICK, V. A.: Cardiovascular Sound in Health and Disease. Baltimore, Williams and Wilkins Co., 1958.
217. MOSS, A. J., LIEBLING, W., and ADAMS, F. H.: The Flush Method for Determining Blood Pressure in Infants; Normal Values During the First Year of Life. Pediat, *21*, 950, 1958.
218. WARNICK, A., and DRAKE, E. H.: A New Intracardiac Pressure Measuring System for Infants and Adults. IRE National Convention Record, pt. 9, 68–73, 1958.
219. VENDRIK, A. J., and VIERHOUT, R. R.: Die Unblutige Registrierung des Blutdrucks: Theoretishe Betrachtungen. Pflüg Arch Ges Physiol, *268*, (5), 496–509, 1959.
220. VON UEXKÜLL, T., and KILLING, F.: Ein Apparat zur Fortlaufenden Unblutigen Registrierung von Puls und Blutdruck. Münch Med Wschr, *101*, 380–382, February 27, 1959.
221. SCHULDT, H. H., and HOFFMAN, F. H.: Bietrage zur Fortlaufenden Umblutigen Registrierung des Arteriellen Blutdruckes am Menschen. Z. Kreislaufforsch, *48*, 101–106, February, 1959.
222. DAVILA, J. C., RIVERA, P. CARILLO, and VOCI, G.: Combined Catheterization of the Heart Utilizing a Modified Transbronchial Technique, Percutaneous Left Ventricular Puncture, and Venous and Arterial Catheterization. Am Heart J, *57*, 514–521, April, 1959.
223. ASHWORTH, A. M., NELIGAN, G. A., and ROGERS, J. E.: Sphygmomanometer for the Newborn. Lancet, *1*, (7077) 801–804, April 18, 1959.
224. RICE, H. N., and POSENER, L. J.: A Practical Method for Measuring Systolic Blood Pressure in Infants, Pediatrics, *23*, 854–860, May, 1959.
225. DOBOSY, J. F., and PROUDFIT, W. L.: A Self-calibrating Blood-pressure Monitoring System. Cleveland Clin Quart, *26*, 134–139, July, 1959.
226. ROBINSON, R. E., III, and EASTWOOD, D. W.: Use of a Photosphygmometer in Indirect Blood Pressure Measurement. Anesthesiology, *20*, 704–707, September–October, 1959.
227. MELVILLE, A. W.: Hydraulic Oscillator for the Dynamic Calibration of Pressure Recording Systems. J Sci Instr, *36*, 422–424, October, 1959.
228. CALLAHAN, A. B., DEGELMAN, J., and LUTZ, B. R.: Systolic Blood Pressure in the Hamster as Determined by a Strain-Gauge Transducer. J Appl Physiol, *14*, 1051–1052, November, 1959.
229. JOHNSON, R. A.: Model 16 Automatic Blood Pressure Measuring Instrument. USAF WADC, Dayton, Ohio, Tech Rept, 59–429, 1–45, December, 1959.
230. NOBLE, F. W.: A Hydraulic Pressure Generator for Testing the Dynamic Characteristics of Blood Pressure Manometers. J Lab & Clin Med, *54*, 897–902, December, 1959.
231. WEISSBACH, G.: Sekundäre Rheographische Blutdruckmessung. Zschr Inn Med, *14*, 1115–1117, December, 1959.
232. CLEMEDSON, C. J., ENGLUND, C. E., and PETTERSSON, H.: A Mechanoelectronic Transducer Blood Pressure Recorder. Acta Physiol Scand, *47*, (suppl. 162) 1–20, 1959.
233. VIERHOUT, R. R., PHILLIPS, E., and VENDRIK, A. J.: Die Unblutige Registrierung des Bludrucks: Blutdruckmessung am Finger. Pflüg, Arch, Ges, Physiol, *268* (5) 510–514, 1959.
234. LEWIS, W. H., Jr.: Procedures in Measurement of Blood Pressure: A Historical Note, Practitioner, *184* 243–247, February, 1960.
235. WEINMAN, J., BICHER, C., and LEVY, D.: Application of a Photoconductive Cell to the Study of Peripheral Circulation in Limbs of Animals and Man. J Appl Physiol, *15*, 317–320, March, 1960.
236. WEISZ, P., ROZA, S., and BARTFAI, J.: Vergleichende Blutdruckmessungen am Menschen Hinsichtlich des "Wahren" (Auf der Initialen Blutstromungberuhenden) Und des Pulsatorischen Systolischen Blutdrucks. Z Ges Inn Med, *15*, 449–451, May 1, 1960.

237. WAGNER, R.: Vereinfachtes Verfahren zur Fortlaufenden Unblutigen Aufschrift des Blutdruckes Beim Menschen. Z Biol, *112*, 67–84, July, 1960.
238. FRY, D. L.: Physiologic Recording by Modern Instruments with Particular Reference to Pressure Recording. Physiol Rev, *40*, 753–788, October, 1960.
239. FRONKOVA, K.: Fortlaufende Indirekte Blutdruckregistrierung. Arch Kreislaufforsch, *33*, 287–309, December, 1960.
240. BERLINER, K., FUJIY, H., HO LEE, D., YILDIZ, M., and GARNIER, B.: The accuracy of Blood Pressure Determinations: a Comparison of Direct and Indirect Measurements. Cardiologia, *37*, 118, 1960.
241. BURCH, G. E., and DEPASQUALE, N.: The Value of Home Recordings of Blood Pressure in the Management of Patients with Arterial Hypertension. Am J M Sc, *240*, 273, 1960.
242. FOLKOW, B.: Role of the Nervous System in the Control of Vascular Tone. Circulation, *21*, 760, 1960.
243. PETERSON, L. H. (editor): Symposium on Regulation of the Cardiovascular System in Health and Disease: Introductions. Circulation, *21*, 739, 1960.
244. PETERSON, L. H.: Regulation of Blood Vessels, Circulation, *21*, 749, 1960.
245. ROTH, G. M., FLOCK, E. V., KVALE, W. F., WAUGH, J. M., and OGG, J.: Pharmacologic and Chemical Tests as an Aid in the Diagnosis of Pheochomocytoma. Circulation, *21*, 769, 1960.
246. RUCH, T. C., and FULTON, J. F.: Medical Physiology and Biophysics, ed. 18. W. B. Saunders Co., Philadelphia, Pa., 1960.
247. SUTTERER, W. F., and WOOD, E. H.: Strain Gauge Manometer: Application to Recording of Intravascular and Intracardiac Pressures. In Medical Physics, *3* (O. Glasser, Ed.), Year Book Publishers, Chicago, Ill., 641–651, 1960.
248. TRAITE, M., WELKOWITZ, W., and DOWNS, R.: Intracardiac Catheter Tip Piezoresistive Pressure Gauge. Rev Sci Instr, *31*, 987–991, September, 1960.
249. WOOD, E. H., SUTTERER, W. F., and CRONIN, L.: Oximetry. In Medical Physics, *3* (O. Glasser, Ed.), Year Book Publishers, Chicago, Ill., 416–445, 1960.
250. RODBARD, S., and CIESIELSKI, J.: Duration of Arterial Sounds. Am J Cardiol, *8*, 18, 1961.
251. BEST, C. H., and TAYLOR, N. B.: The Physiological Basis of Medical Practice, ed. 7. Williams & Wilkins Co., Baltimore, Md., 1961.
252. DOCK, W.: Inspiratory Traction on the Pericardium; the Cause of Pulsus Paradoxus in Pericardial Disease. AMA Arch Int Med, *108*, 837, 1961.
253. SCHWAN, H. P.: Biomedical Electronics—Past and Present. Inst Radio Eng Int Comm Rec, *9*, (9) 155–160, 1961.
254. SULLIVAN, G.: Measurement of Respiration and Ventilation in Aerospace Environment. Amer Rocket Soc Tech Paper (61–160–1854), 1961.
255. Instruments Abstracts, British Sc Inst Research Assoc, Surgical Equip.-Design, *165* 71–73, September, 1962.
256. Blood Pressure Taken, Recorded Automatically. Elec Design, *10* (7) 28, 1962.
257. Recording Physiological Measurements for Data Processing. Tech News Bull Bar Study, *46* (6) 76–77, June, 1962.
258. NEWELL, D. C.: A Pressure Sensitive Crystal Oscillator. Amer J Ophthol, *52*, 984–989, 1961.
259. Strain Gauge Pickup Measures Blood Pressure. Mach Design, *34* (18) 93, August 2, 1962.
260. WOLFF, H. S.: The Future of Medical Electronics and Instruments, Instr Pract, *16* (7) 881–885, July, 1962.
261. HATHAWAY, C. M.: Electrical Instruments for Strain Analysis. Exp Stress Anal, I, *1* 83, 1962.
262. LANGER, B. F.: Design and Applications of a Magnetic Strain Gauge. Exp Stress Anal, I, *2*, 82, 1962.
263. LANGER, B. F., and WOMMACK, K. L.: Magnetic-Coupled Torquemeter. Exp Stress Anal, II, *2* 11, 1962.
264. MAGEE, G. M., and FERGUSON, R.: Application of Electric Measuring Equipment in Railroad Research. Exp Stress Anal, II, *1* 1, 1962.
265. The Mechcano-Electronic Transducer Tube, Type 5734. Radio Corporation of America Tube Handbook, 1–2, 1962.
266. MEHAFFEY, W. R., VAN SCOYOC, J. N., and SCHOVER, D. S.: A Direct-coupled Amplifier for Recording Dynamic Strain. Exp Stress Anal, VI, *1*, 44, 1962.
267. PICKERING, W. H.: Reluctance Gauges for Telemetering Strain Data. Exp Stress Anal IV, *2*, 74, 1962.
268. RENO, H.: Instruments for Aircraft Strain Analysis. Exp Stress Anal, II, *2*, 106, 1962.
269. ROBERTS, H. C. Electric Gauging Methods: Their Selection and Application. Exp Stress Anal, IV, *2*, 89, 1962.

270. SCHAEVITZ, HERMAN: The Linear Variable Differential Transformer. Exp Stress Anal, IV, *2*, 79.
271. WELLER, R., and SHEPARD, B. M.: Displacement Measurement by Mechanical Interferometry. Exp Stress Anal, VI, *1*, 35, 1962.
272. ZAALBERG, J. J.: Circuit for Condenser Microphones with Low Noise Level. Philips Tech Rev, *9*, 12, 357, 1962.
273. Dorlands Illustrated Medical Dictionary, ed. 23. W. B. Saunders Co., Philadelphia, Pa. and London, Eng., 1957.
274. GRAY, H.: Anatomy of the Human Body, ed. 26. Charles Mayo Goss, Lea and Febiger, Philadelphia, Pa., 1954.
275. GUYTON, A. C.: Textbook of Medical Physiology. W. B. Saunders Company, Philadelphia, Pa., and London, Eng., 1956.
276. BURCH, G. E., and DEPASQUALE, N. P.: Primer of Clinical Measurement of Blood Pressure. C. V. Mosby Company, St. Louis, Mo., 1962.
277. KRATOCHVIL, C. H.: Physiologic Instrumentation of Man During Flight. Bioastrionics Corps: Advances in Research, U.S. School of Aviation Medicine, Randolph AFB, Texas, March, 1950.
278. WOOD, E. H.: A Single Scale Absolute Reading Ear Oximeter. Proc Staff Meet, Mayo Clin, *25*, 384–391, July 5, 1950.
279. WOOD, E. H., et al: Measurement of Blood Content and Arterial Pressure in the Human Ear. Proc Staff Meet, Mayo Clin, *25*, 398–405, July 5, 1960.
280. SCHOTZ, S., et al: The Ear Oximeter as a Circulatory Monitor. Prel Report, Anesthesiology, *19* 386–393, 1958.
281. STARR, I., et al: Studies Made by Simulating Systole at Necropsy, Part IV, Circulation, *9*, 648, May 1954.
282. BROTMACHER, L.: Evaluation of Derivation of Cardiac Output from Blood Pressure Measurements. Circulation Res V (6) 589–593, November, 1957.
283. ZUIDEMA, G. D., EDELBERG, R., and SALZMAN, E. W.: A Device for Indirect Recording of Blood Pressure. J Appl Physiol, *9* (1) 132–134, 1956.
284. ZUIDEMA, G. D., EDELBERG, R., and SALZMAN, E. W.: A Device for the Indirect Recording of Blood Pressure. WADC, Aero Medical Lab, WADC Technical Note No. 55–427 (AD 93 634), September, 1955.
285. ZUIDEMA, G. D., and EDELBERG, R.: Research Uses for Indirect Blood-Pressure Recorder. J Appl Physiol, *9* (3) 501–502, November, 1956.
286. BLAQUIER, P., and HOOBLER, S. W.: A New Blood-Pressure Cuff for Self-Determination of the Blood Pressure. Univ Mich Med Bull, *23*, 356–365, October, 1957.
287. CURRENS, J. H., BROWNELL, G. L., and ARONOU, S.: An Automatic Blood-Pressure-Recording Machine. New England J Med, *256* (17) 780–784, 1957.
288. JOHNSON, R. A.: Model 16 Automatic Blood Pressure Measuring Instrument. Systems Research Laboratories, Inc., WADC TR 59–429 Contract No. AF 33(616)–5829, December, 1959.
289. ROBINSON, R. E., and EASTWOOD, D. W.: Use of Photo-Sphygmometer in Indirect Blood Pressure Measurements. Anesthesiology, 704, September-October, 1959.
290. TRAITE, M., GERMAIN, L. M., and PRATT, A. W.: Systolic and Diastolic Blood Pressure on a Finger, Paper presented at 15th Annual Conf on Eng in Med and Bio, November, 1962.
291. Blood Pressure Taken, Recorded Automatically. Elec Design, *10* (7) 28, March 29, 1962.
292. An Automatic Finger Blood-Pressure Recorder. The Lancet, *2*, 1178–1180, November 25, 1961.
293. Results of the First United States Manned Orbital Space Flight. NASA, Manned Spacecraft Center, 40–44, February 20, 1962.
294. SHIRER, H. W.: Blood-Pressure Measuring Methods. IRE Trans, BME–9, April 1962.
295. ADAMS, R., and CORELL, R. W.: Cuffless, Noncannula, Continuous Recording of Blood Pressure. Surgery, *47*, 46–54, 1960.
296. SALISBURY, P. F., and WICHMANN, T.: New Method for the Indirect Measurement of Blood Pressure. Paper presented at Inst Soc of Am Conf, Los Angeles, Calif., September 11–15, 1961.
297. SIMONSON, E., and NAKAGAWA, K.: Effect of Age on Pulse Wave Velocity and Aortic Ejection Time in Healthy Men and in Men with Coronary Artery Disease. Circulation, *22*, 126, 1960.
298. LANDOWNE, M.: A Method Using Induced Waves to Study Pressure Propagation in Human Arteries. Circulation Res, *5*, 594, 1957.
299. McDONALD, D. A.: Blood Flow in Arteries. Williams and Wilkins, Baltimore, Md., 1960.
300. LANDOWNE, M.: Wave Propagation in Intact Human Arteries. Federation Proc, *12*, 82, 1953.
301. PRESSMAN, G. L., and NEWGARD, P. M.: A Transducer for the Continuous External Measurement of Arterial Blood Pressure. IEEE Trans on Bio-Med Electron, April 1963.

U.S. GOVERNMENT PRINTING OFFICE: 1964 O—724-177